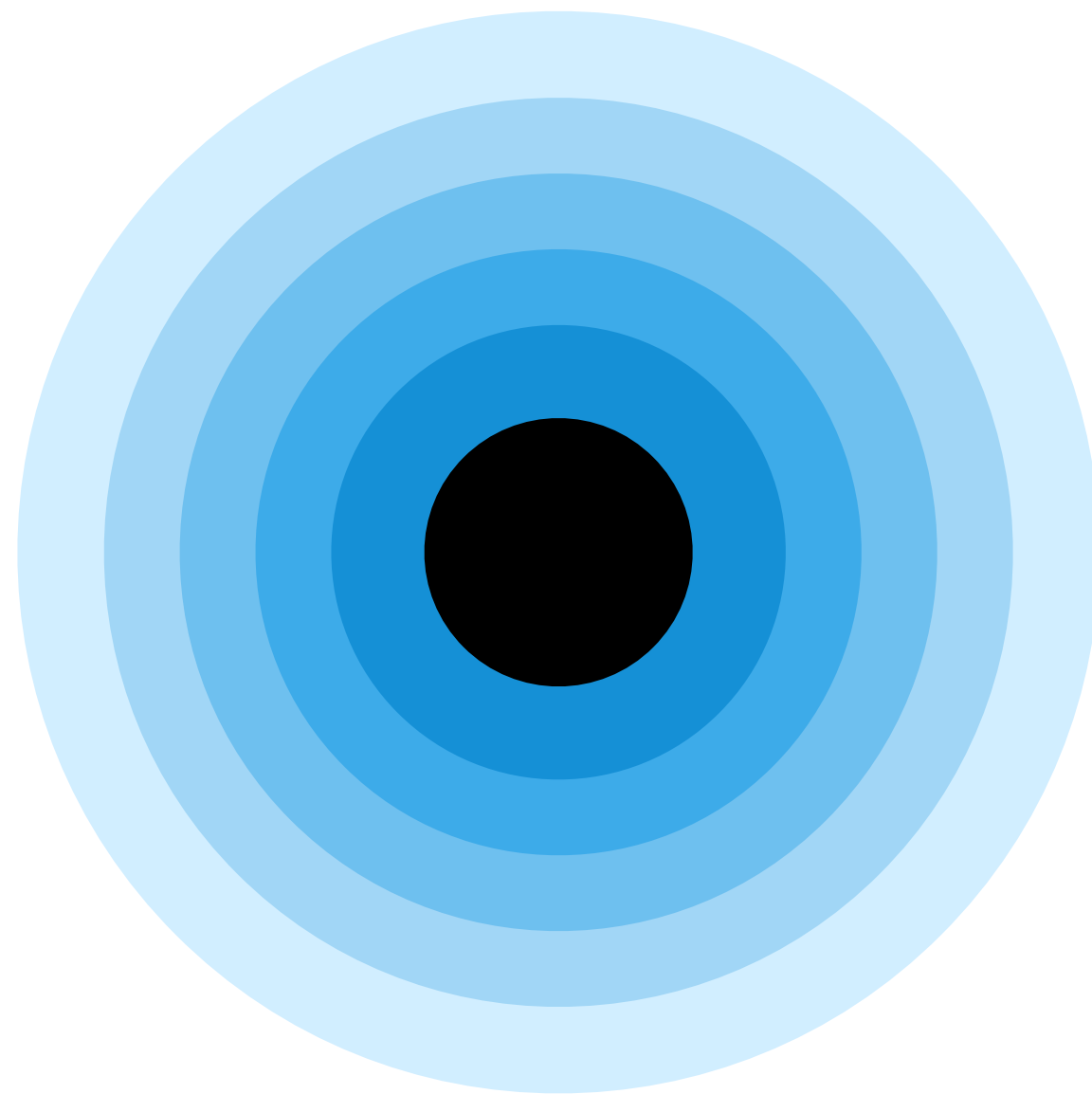


Looking for Dark Matter around Primordial Black Holes



Bradley J Kavanagh [he/him]

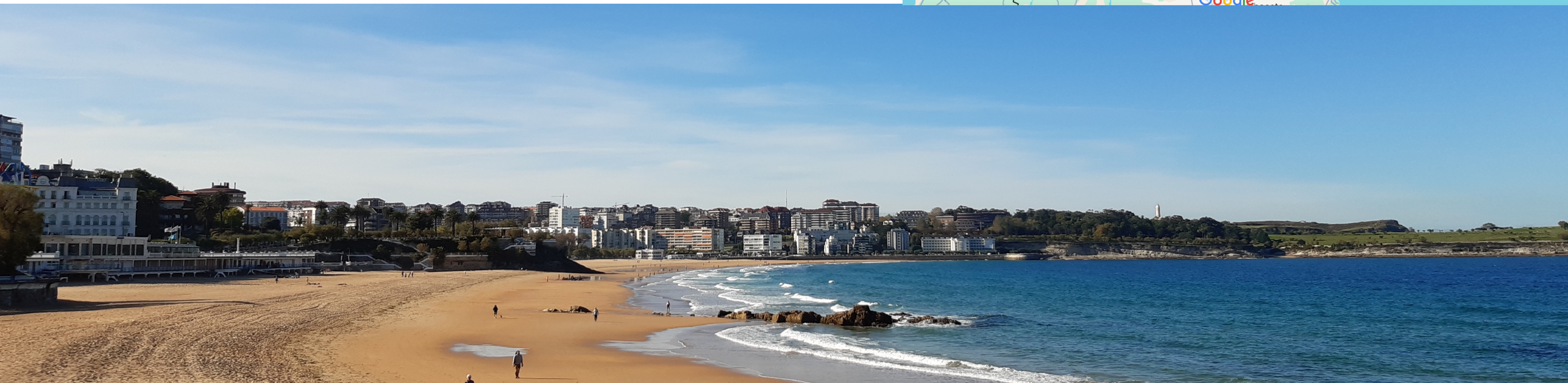
Instituto de Física de Cantabria (CSIC-UC)

kavanagh@ifca.es

Phenomenology of Primordial Black Holes
MITP, 24th July 2026



Keep an eye out for our biannual conference:
Dark Matter 2027: From the Smallest to the Largest Scales
...Coming ~June 2027
[Previous edition: [DM2025](#)]

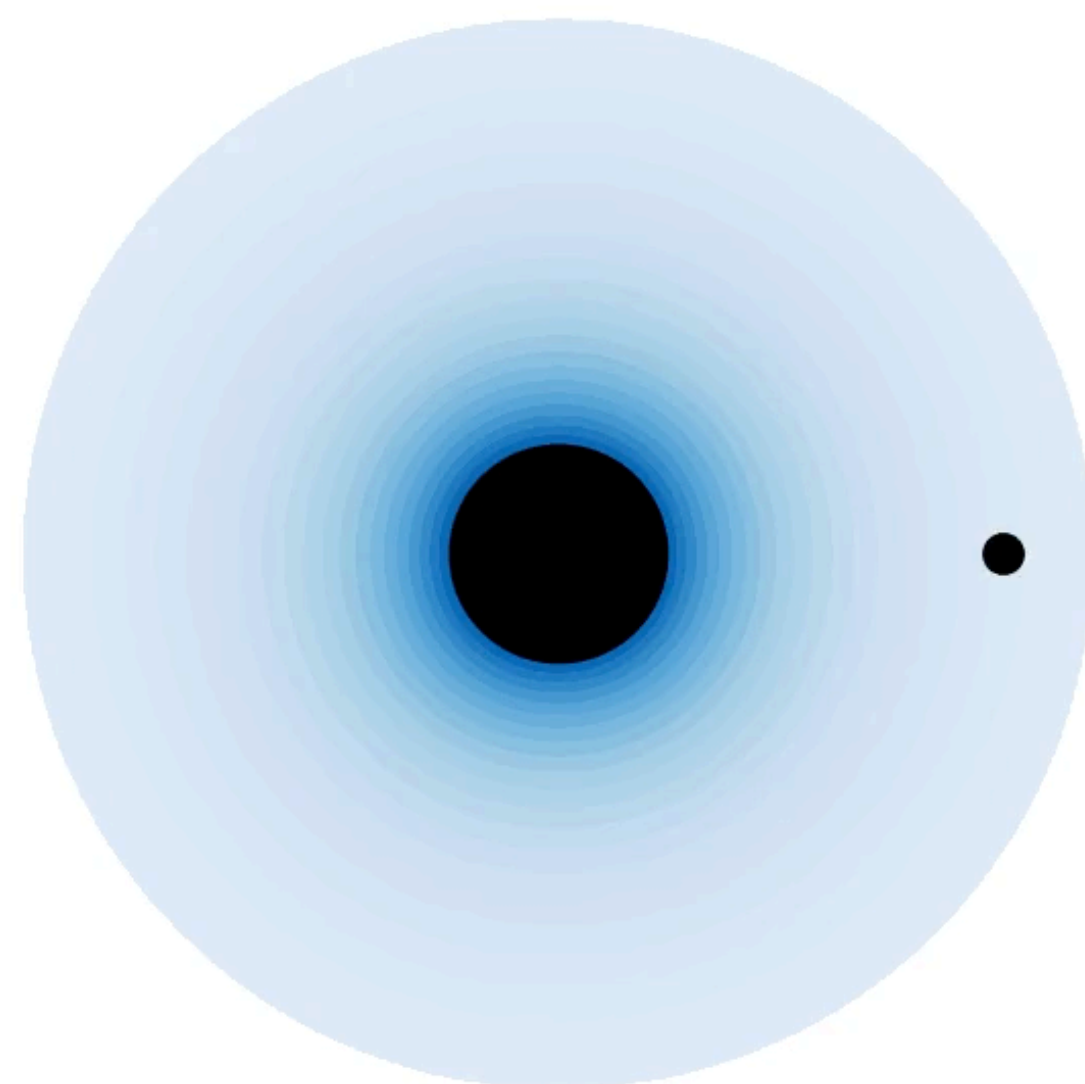




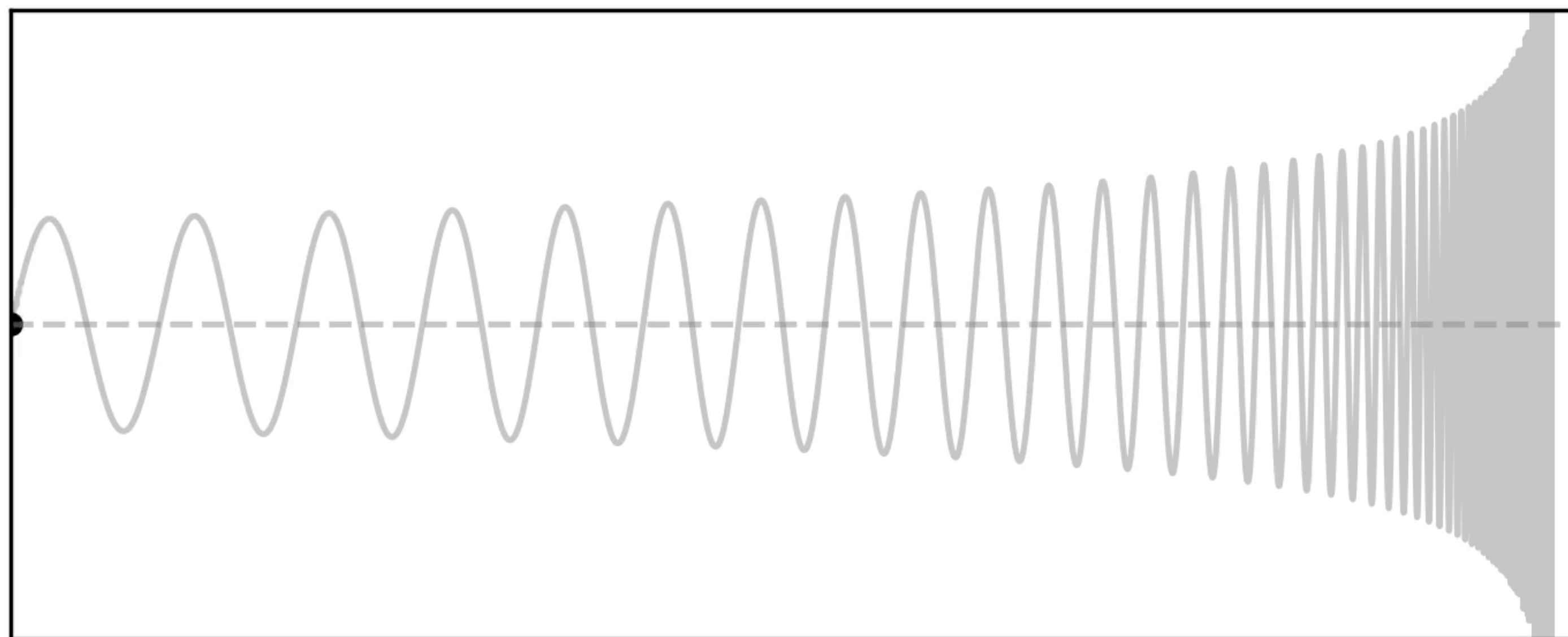
GW Strain, $h(t)$



Time, t



GW Strain, $h(t)$



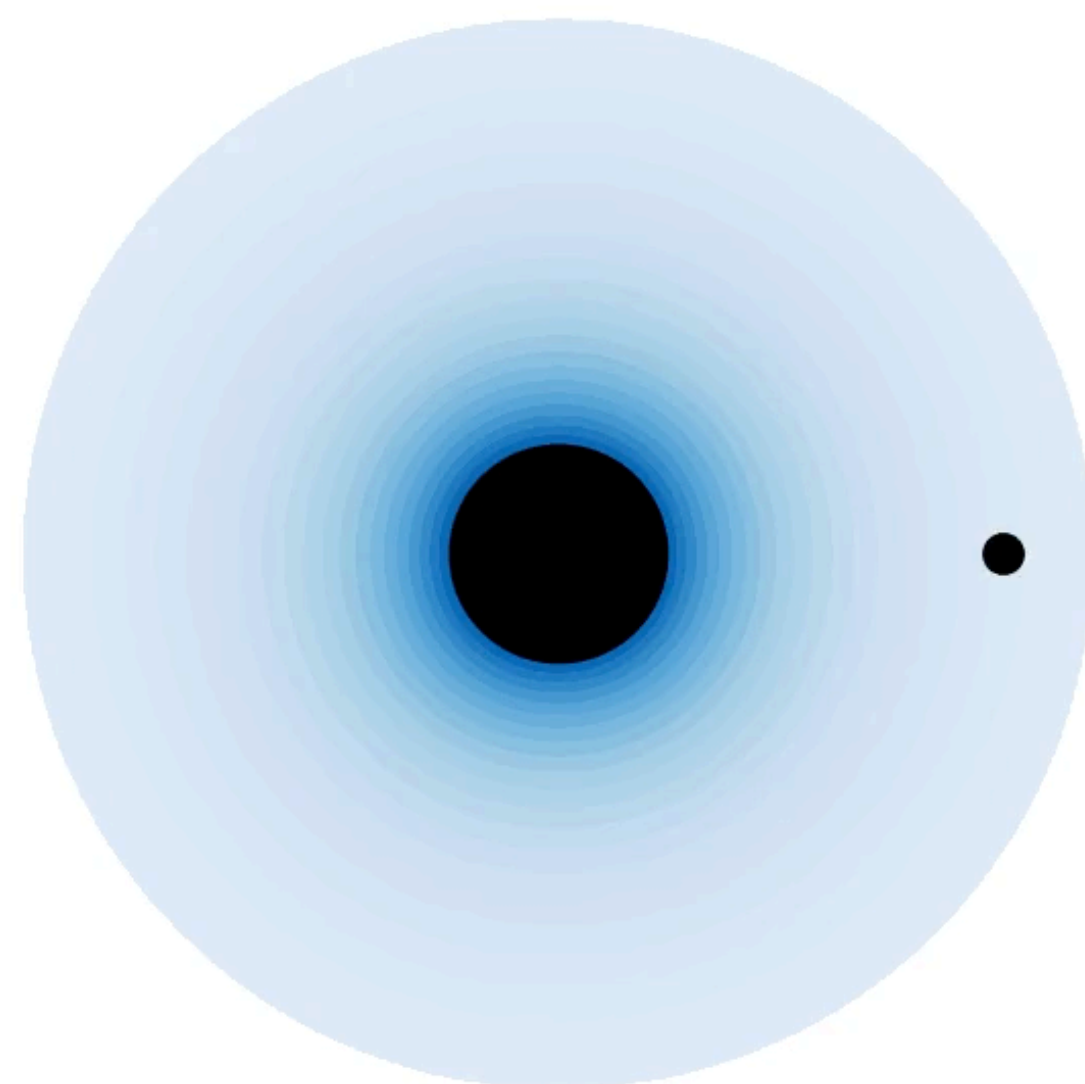
Time, t



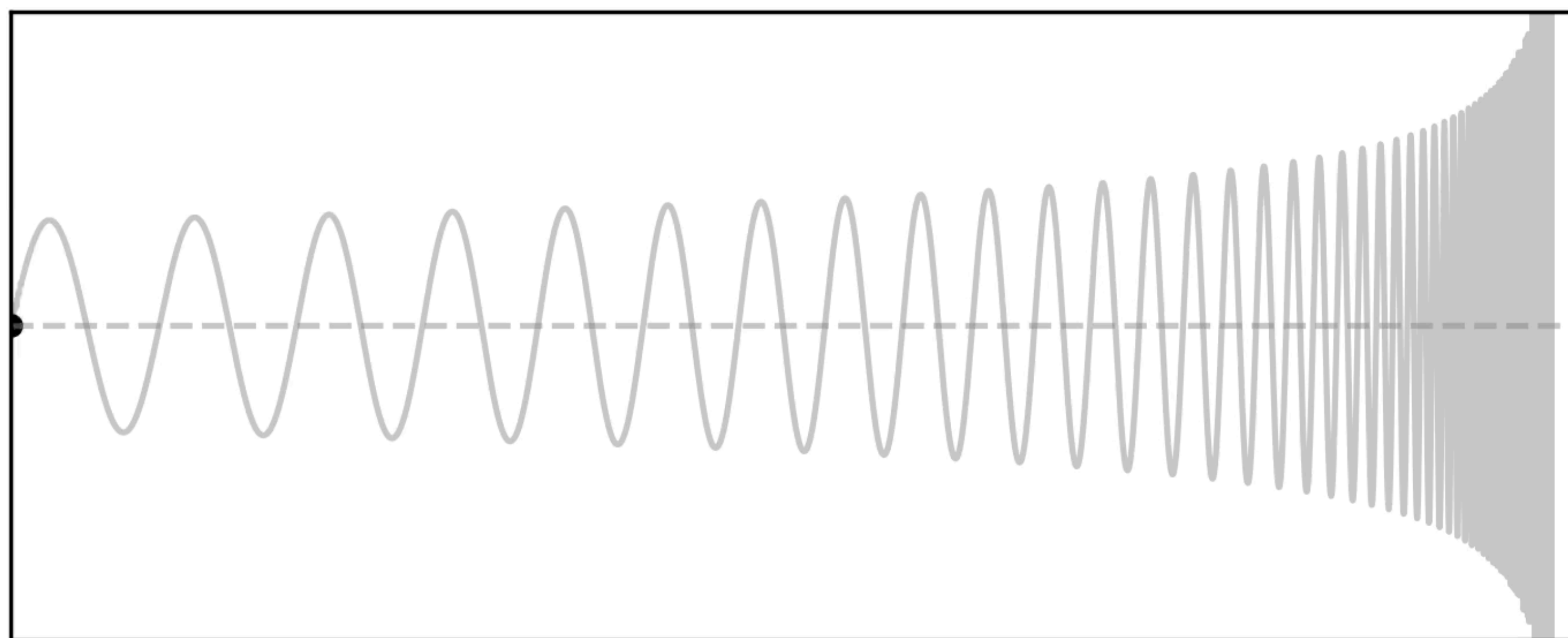
GW Strain, $h(t)$



Time, t



GW Strain, $h(t)$



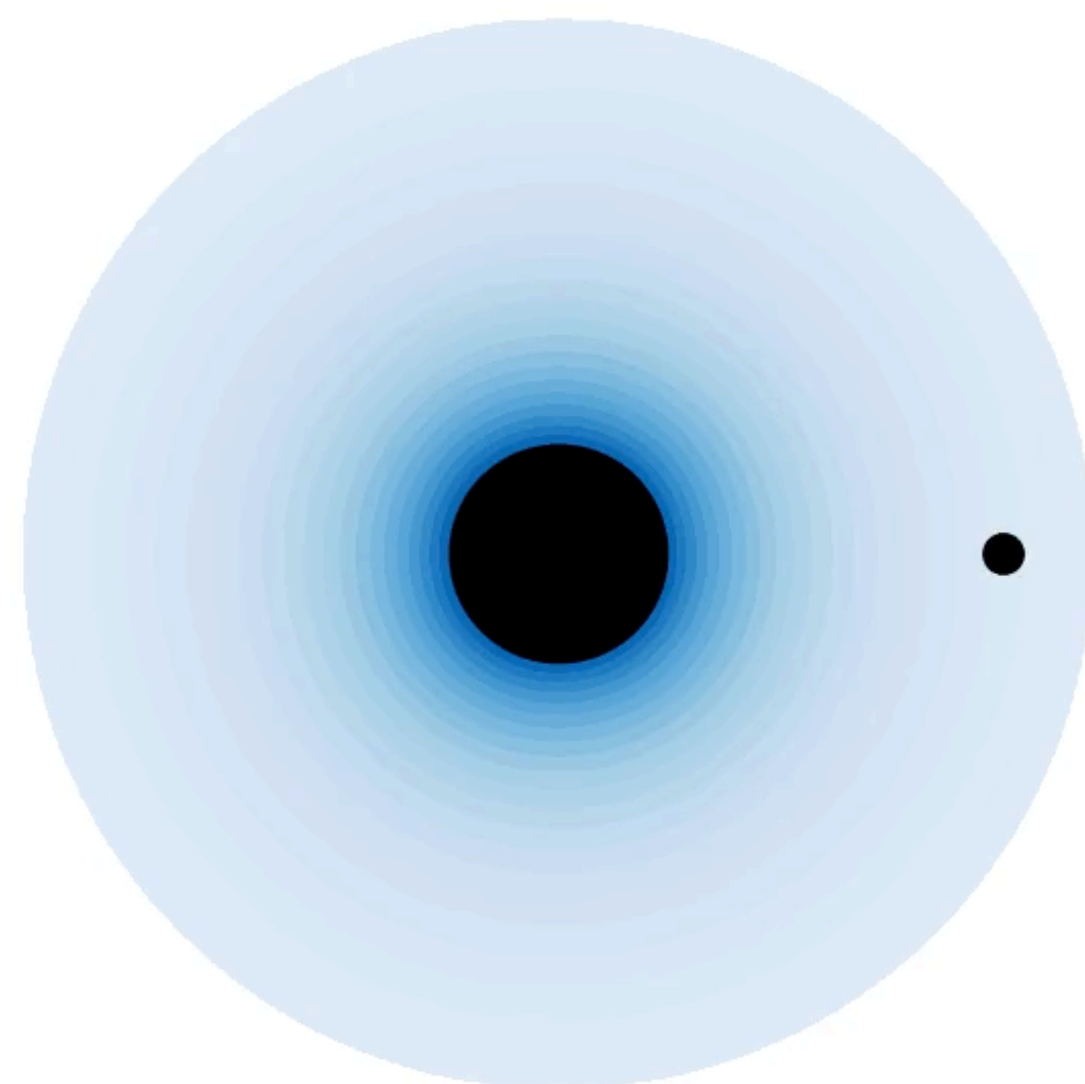
Time, t



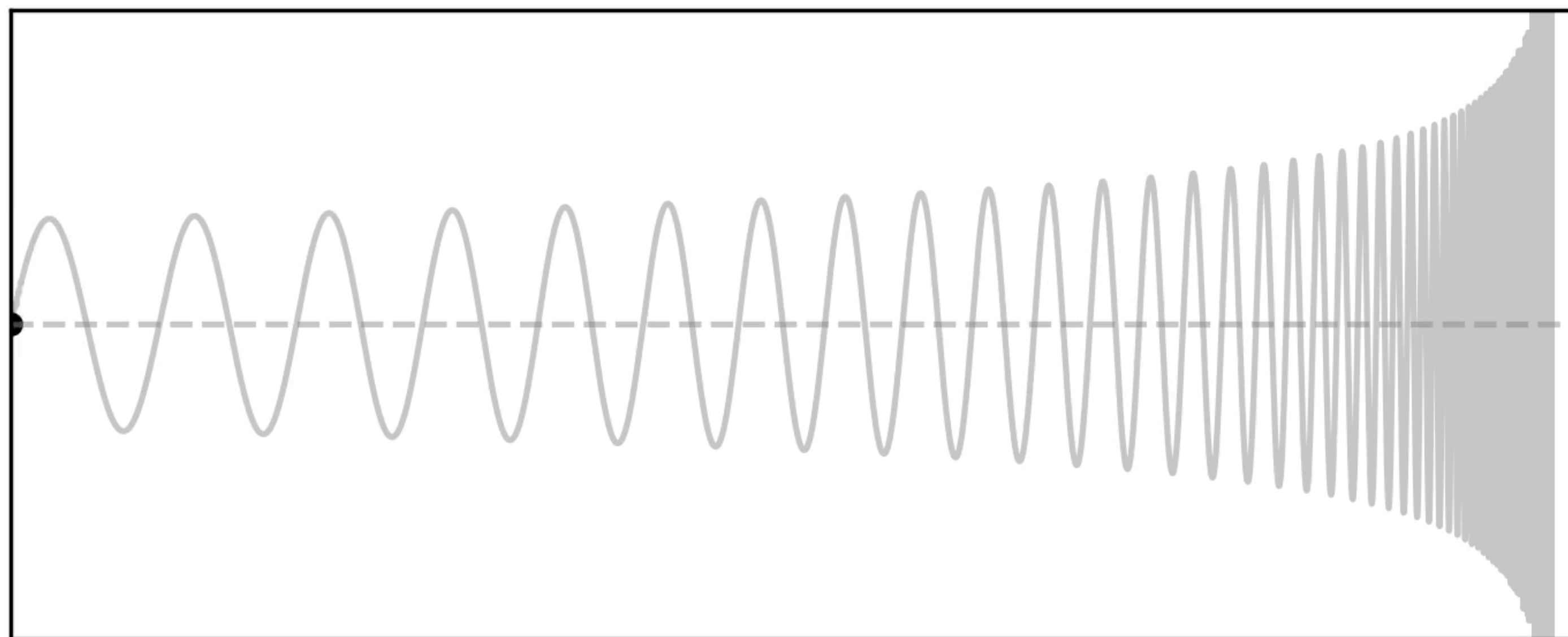
GW Strain, $h(t)$



Time, t

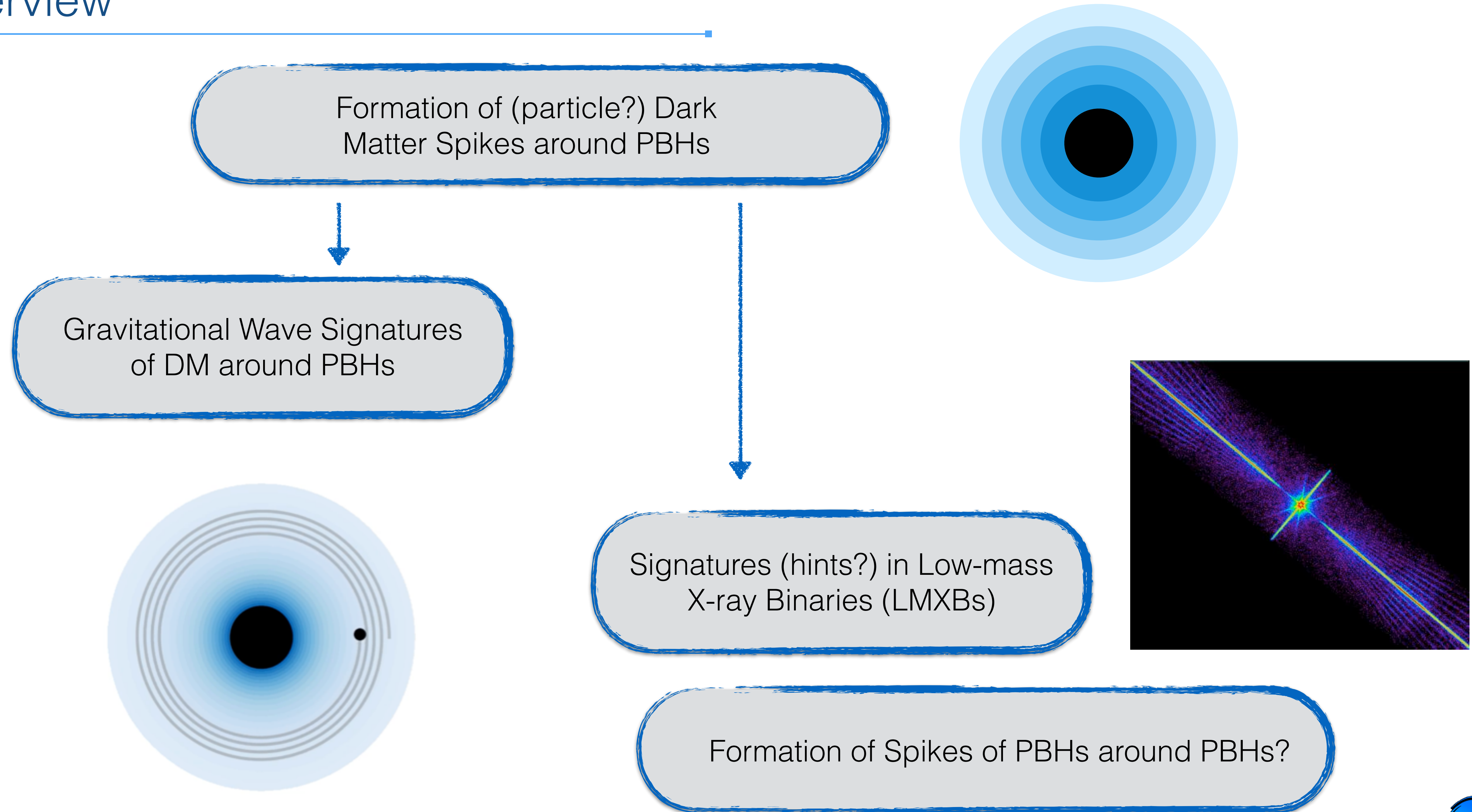


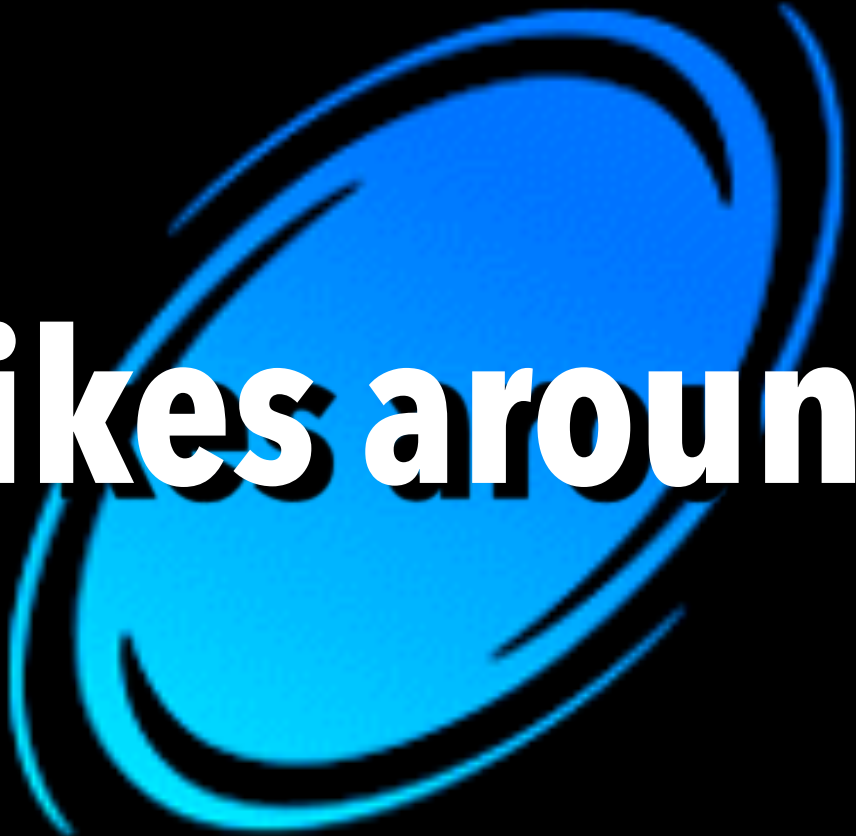
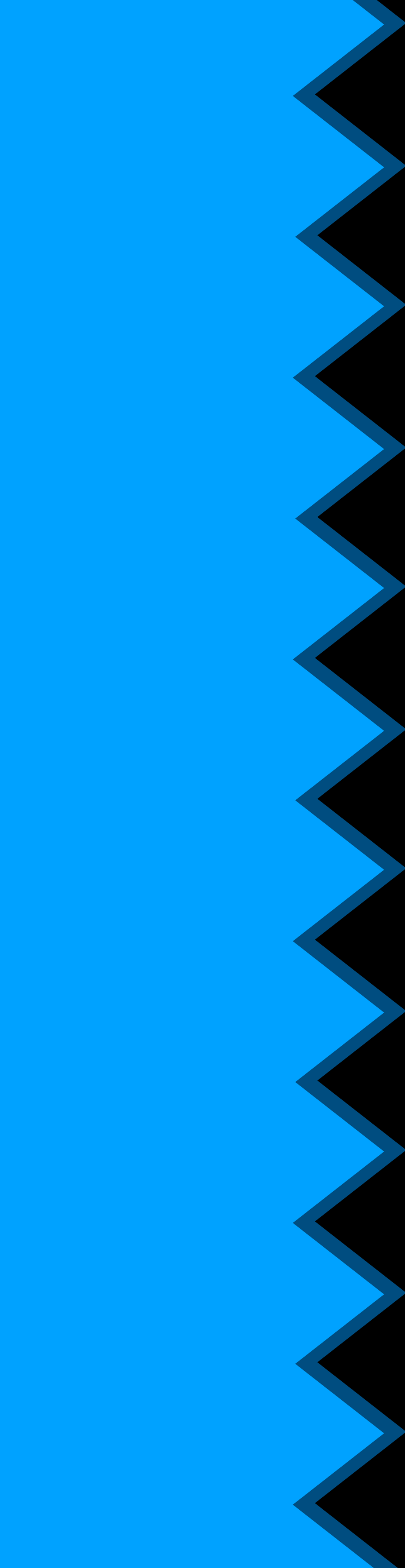
GW Strain, $h(t)$



Time, t

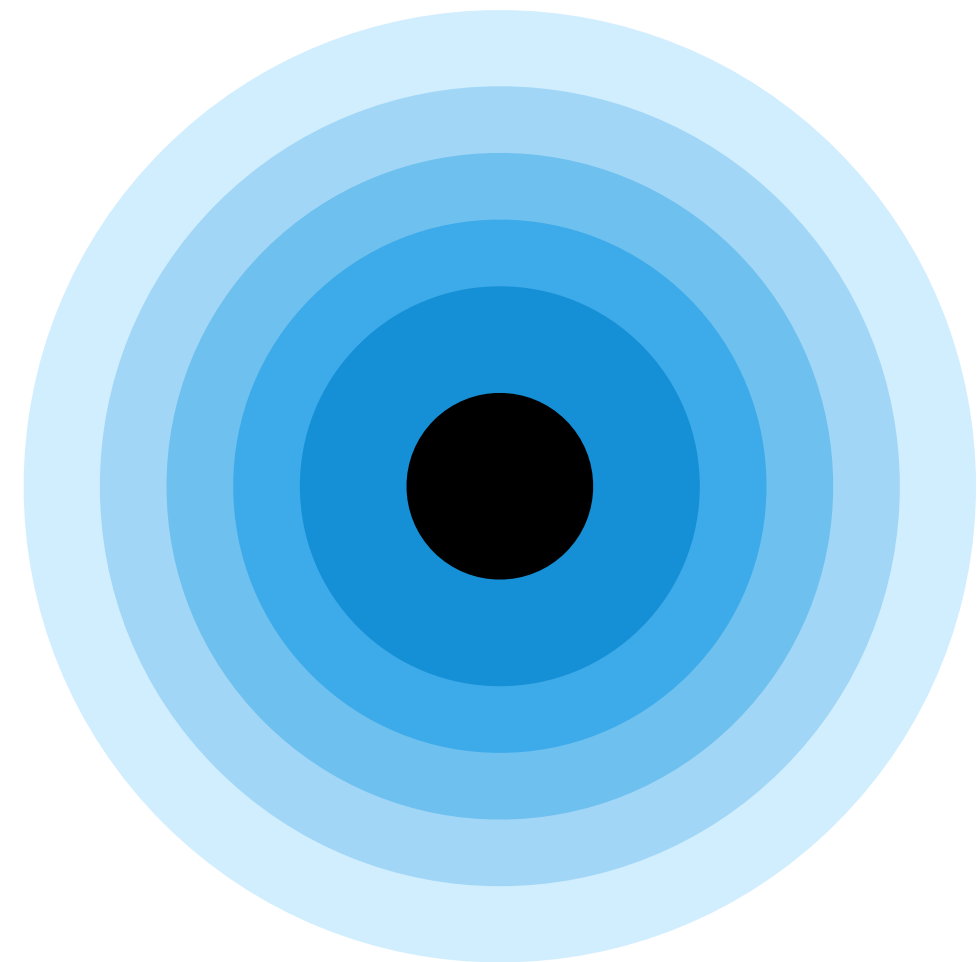
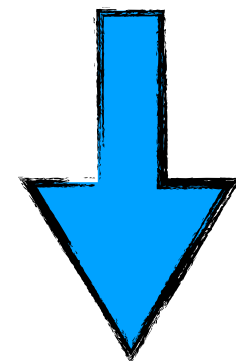
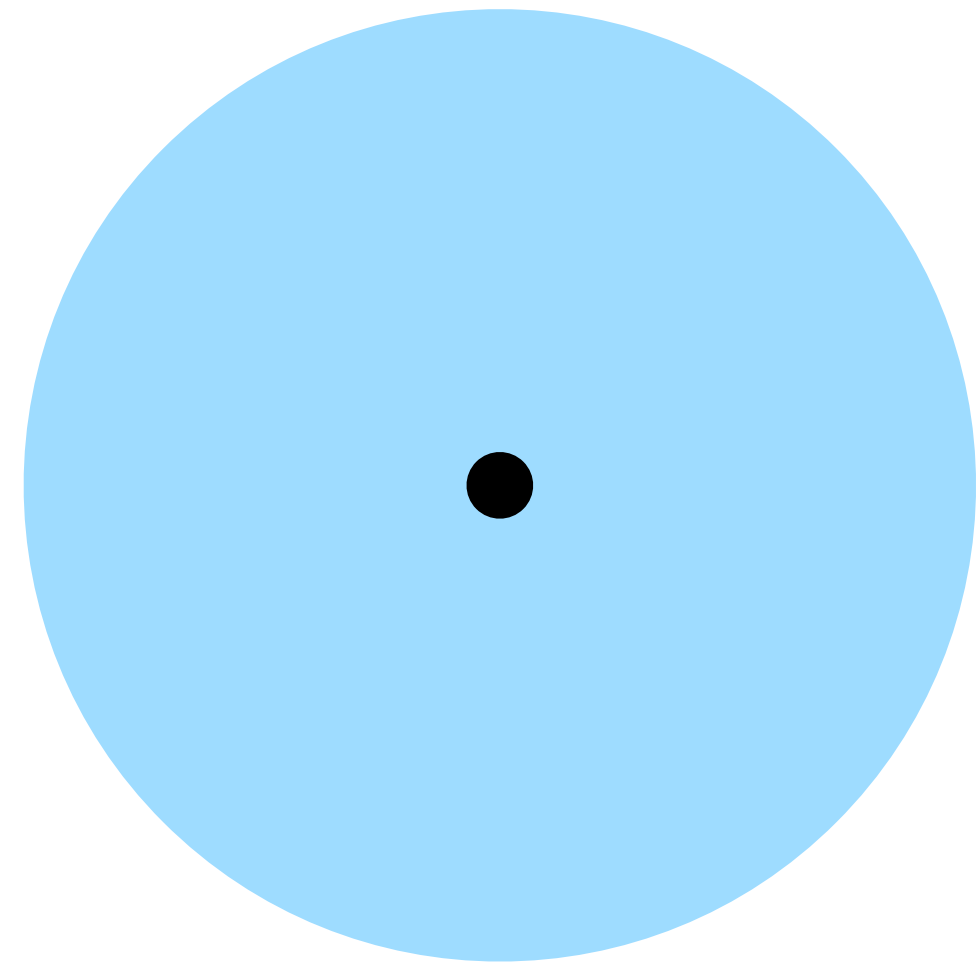
Overview





DM Spikes around PBHs

Dark Matter Spikes



‘**Spikes**’ or ‘**dresses**’ of cold, particle-like DM may form around BHs:

Around BHs which form from large density fluctuations in the early Universe (i.e. Primordial Black Holes)

“**PBH scenario**”

[[Bertschinger \(1985\)](#), [astro-ph/0608642](#), [1901.08528](#), ...]

From the slow (‘adiabatic’) growth of a BH at the centre of a DM halo

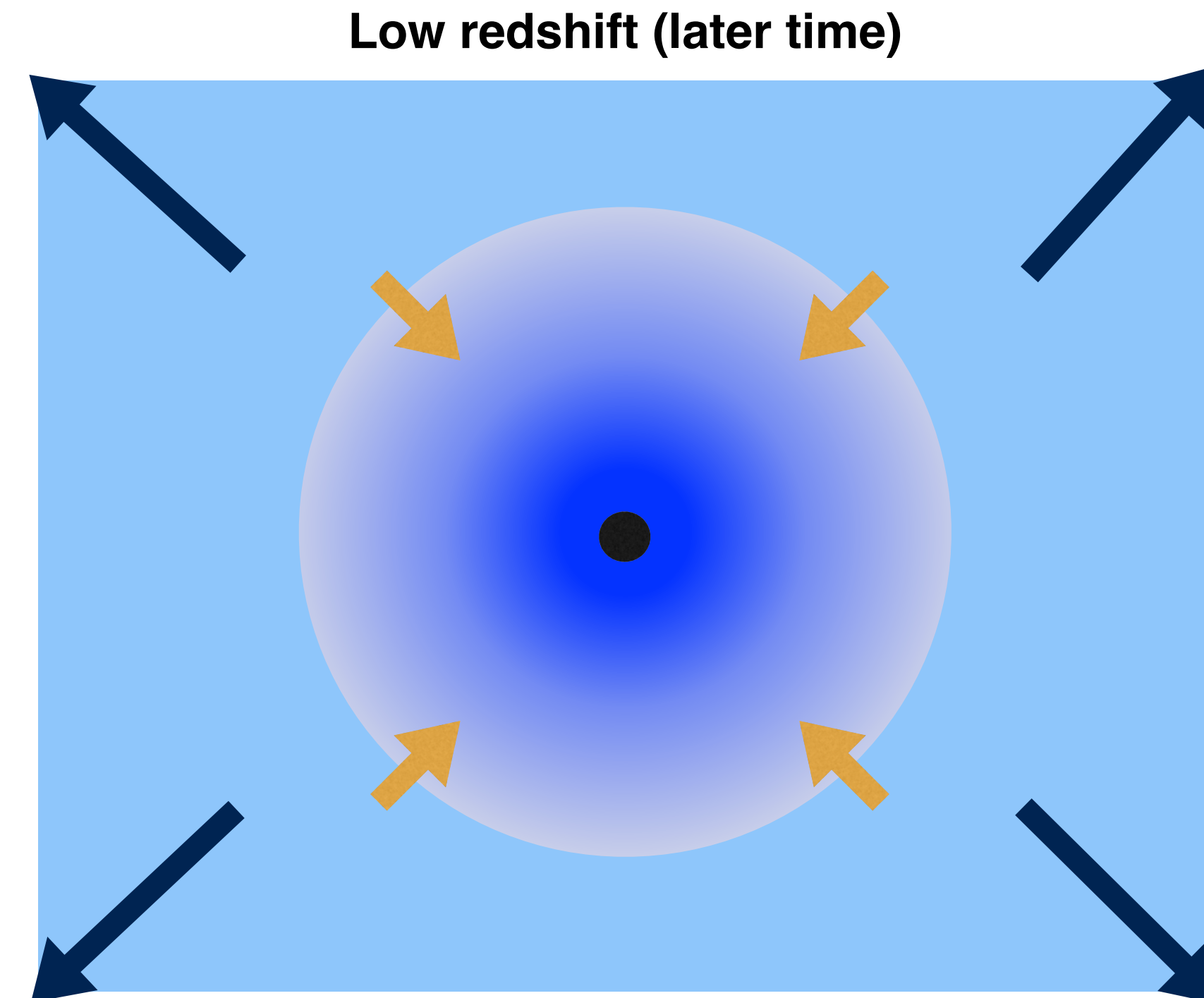
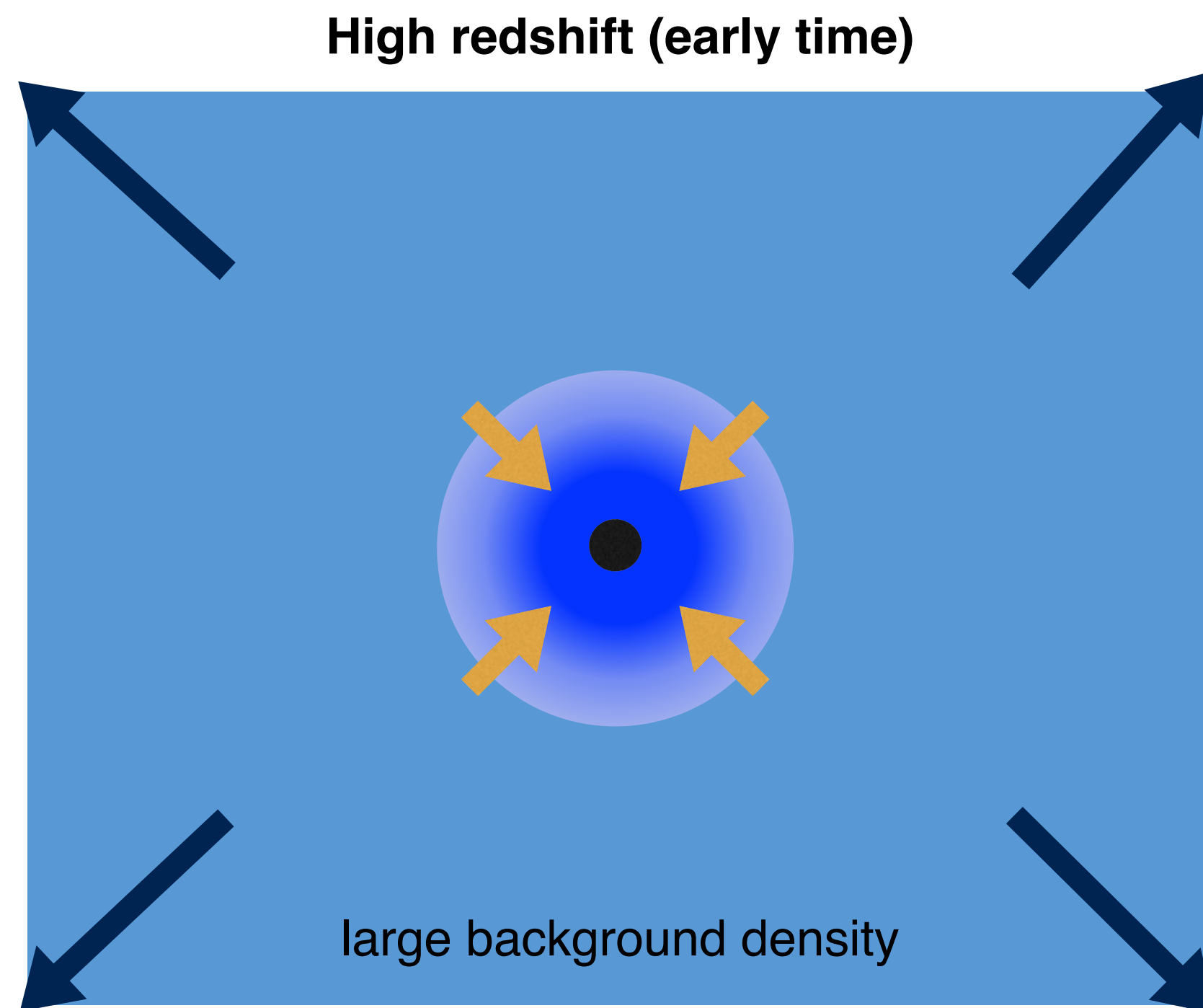
“**Astrophysical scenario**”

[[astro-ph/9906391](#), [astro-ph/0509565](#), [1305.2619](#), ...]

Dark Matter around PBHs

[[Bertschinger \(1985\)](#), Mack et al., [astro-ph/0608642](#),
Ricotti, [0706.0864](#), Sten Delos et al., [1712.05421](#),
Adamek et al., [1901.08528](#), Boudaud et al., [2106.07480](#), ...]

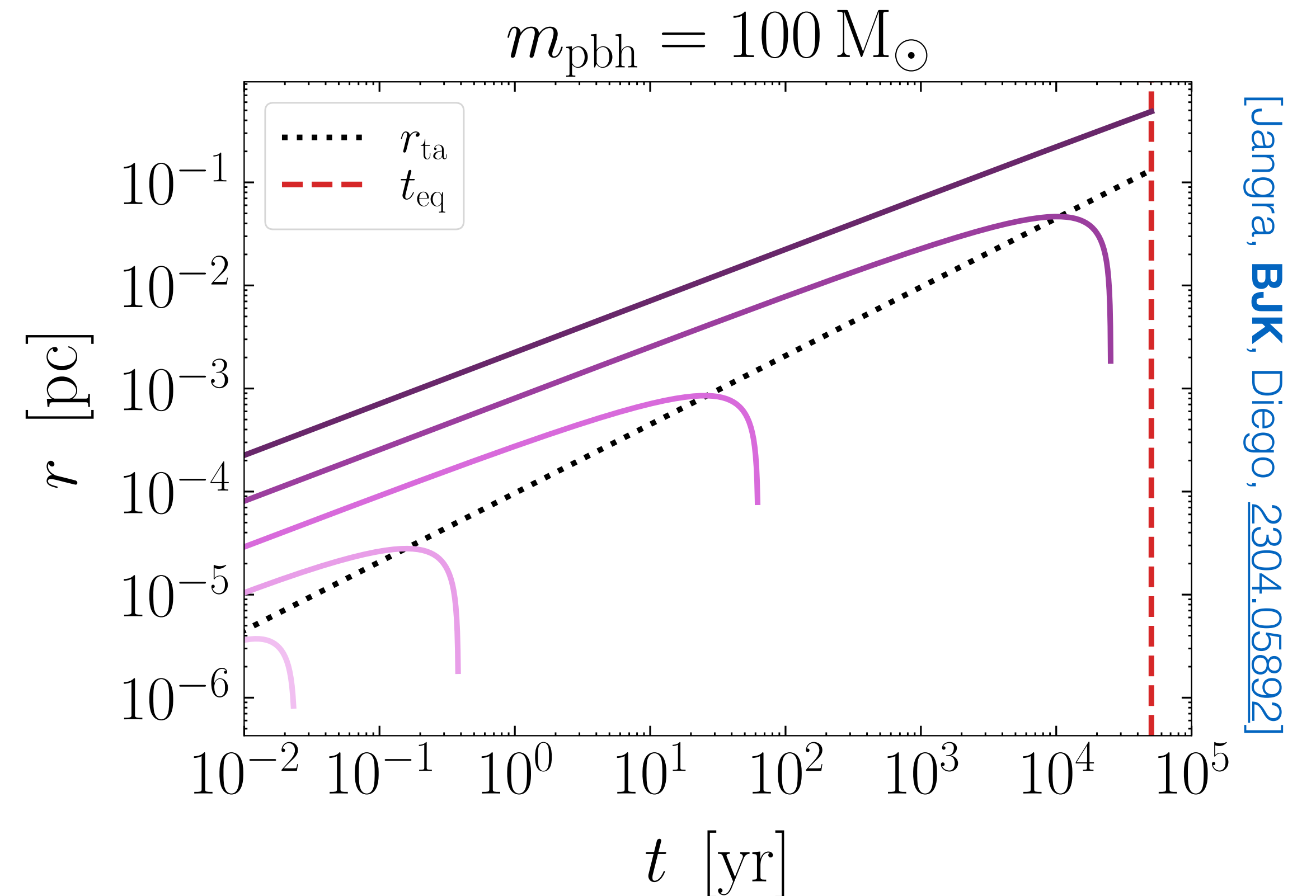
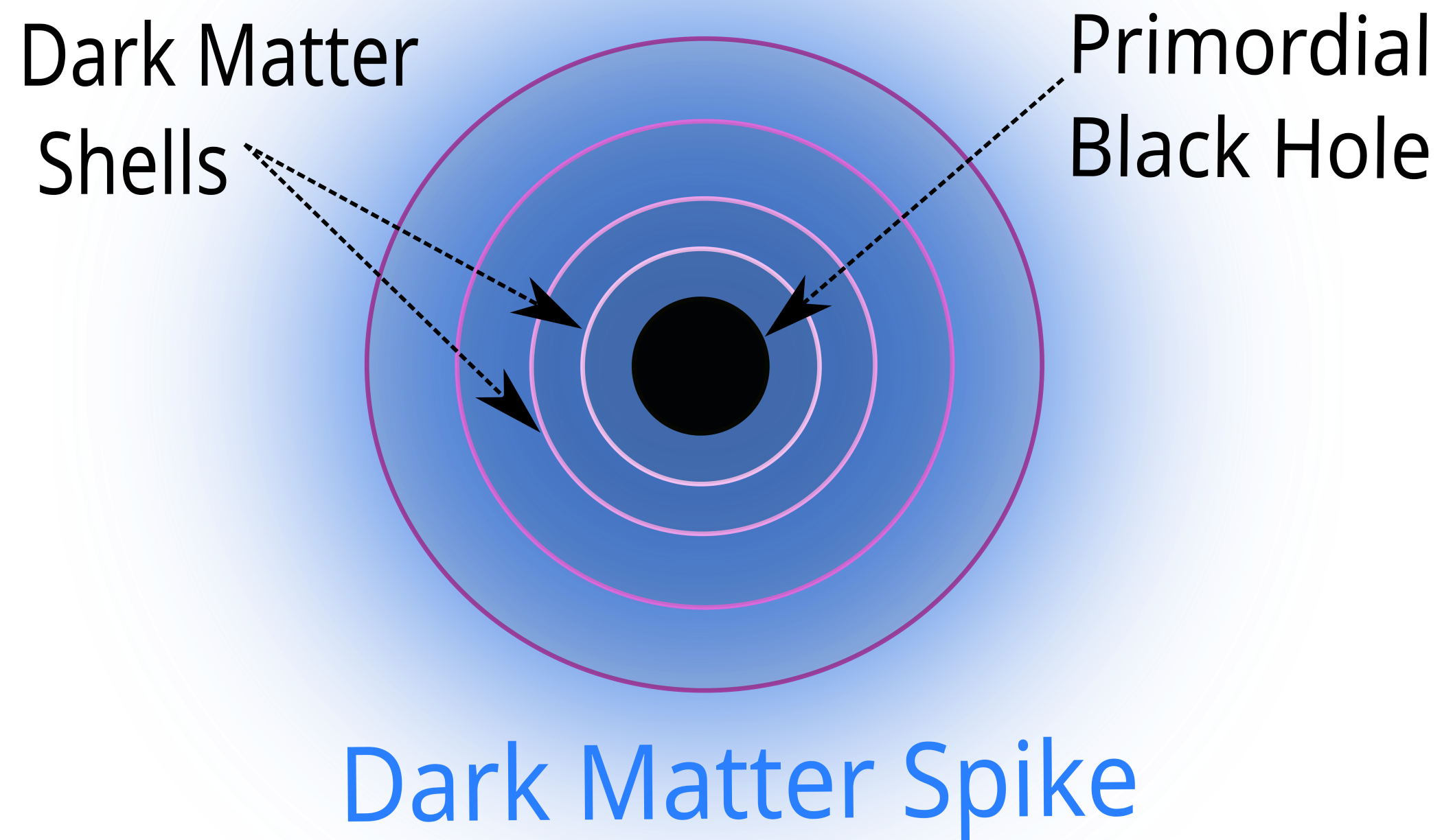
Primordial Black Holes (PBHs) seed the formation of DM spikes:



Dark Matter Turn-around

[[Bertschinger \(1985\)](#), Mack et al., [astro-ph/0608642](#),
Ricotti, [0706.0864](#), Sten Delos et al., [1712.05421](#),
Adamek et al., [1901.08528](#), Boudaud et al., [2106.07480](#), ...]

Follow the turn-around of shells of DM at different radii: $\ddot{r} = \frac{\ddot{a}}{a}r - \frac{GM_{\text{BH}}}{r^2} \Rightarrow a_{\text{ta}} \propto r^{3/4}$



At the moment of turn-around, the density of the shell is $\rho_{\text{ta}}(r) \simeq \rho(t_{\text{ta}}(r)) \sim r^{-9/4}$

Dark Matter Spikes

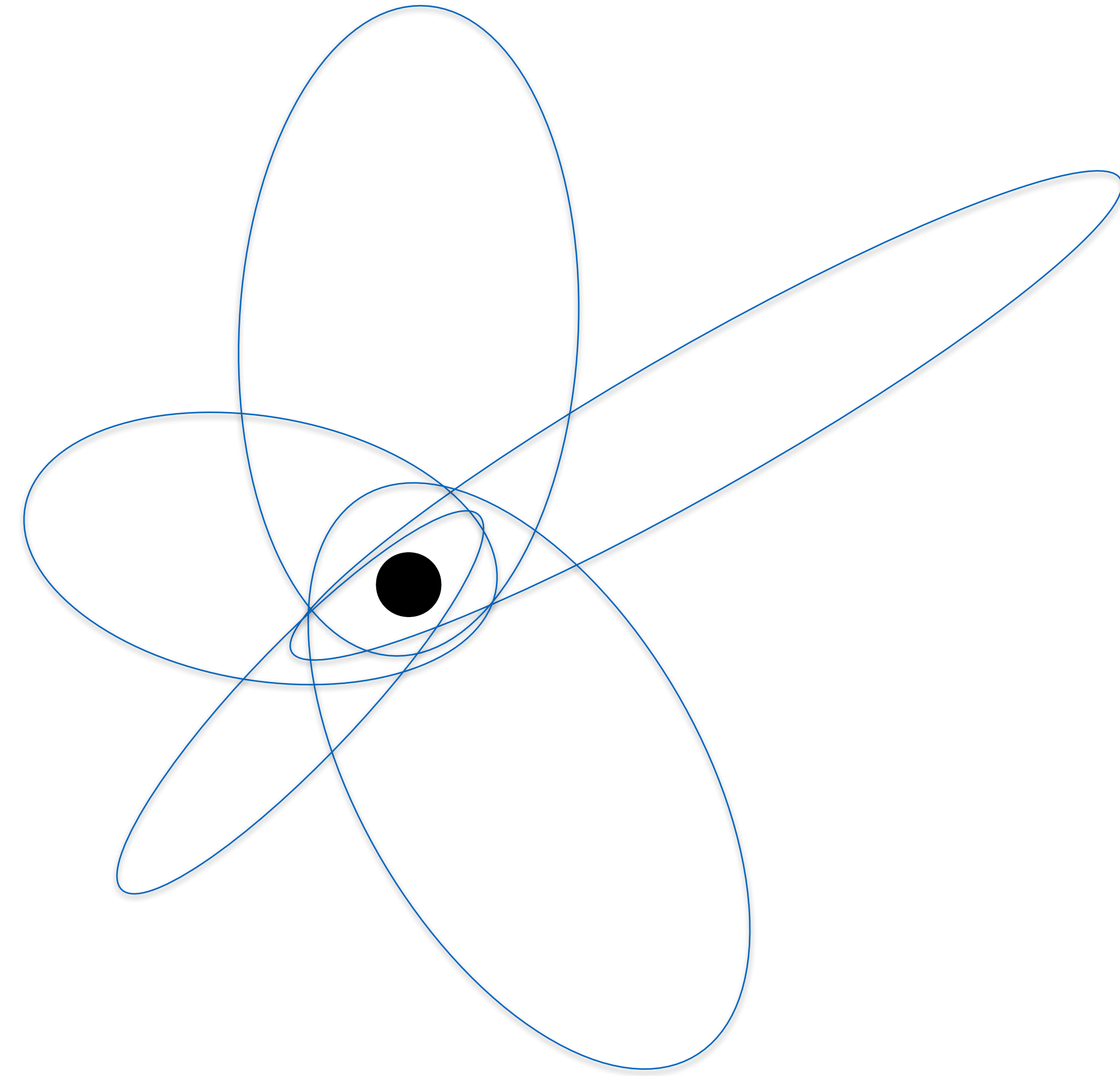
Consider **thermal DM**: they typically possess enough angular momentum to enter stable orbits around the central PBH and avoid capture

The density profile will depend on the distribution of orbital parameters, the velocity distribution (Maxwell-Boltzmann) and density at turnaround:

$$\rho(r) r^2 \propto \int dr_{\text{ta}} r_{\text{ta}}^2 \rho_{\text{ta}} \int d^3v f(v) \times \text{all possible orbits}$$

After $\sim$ free-fall time, a stable DM spike with $\rho(r) \sim r^{-9/4}$ is formed around the PBH

[e.g. Eroshenko, [1607.00612](#)]

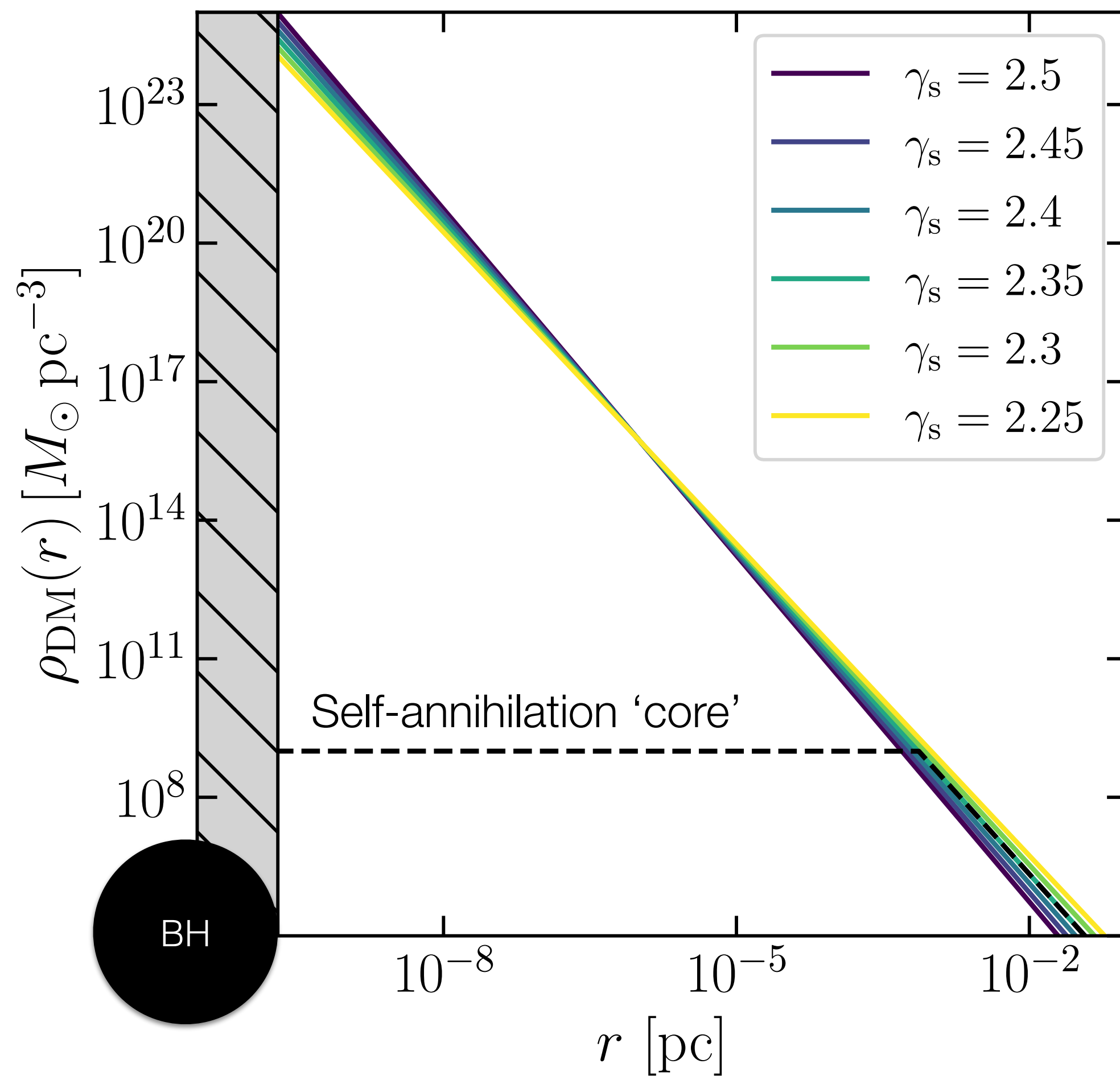


Complications

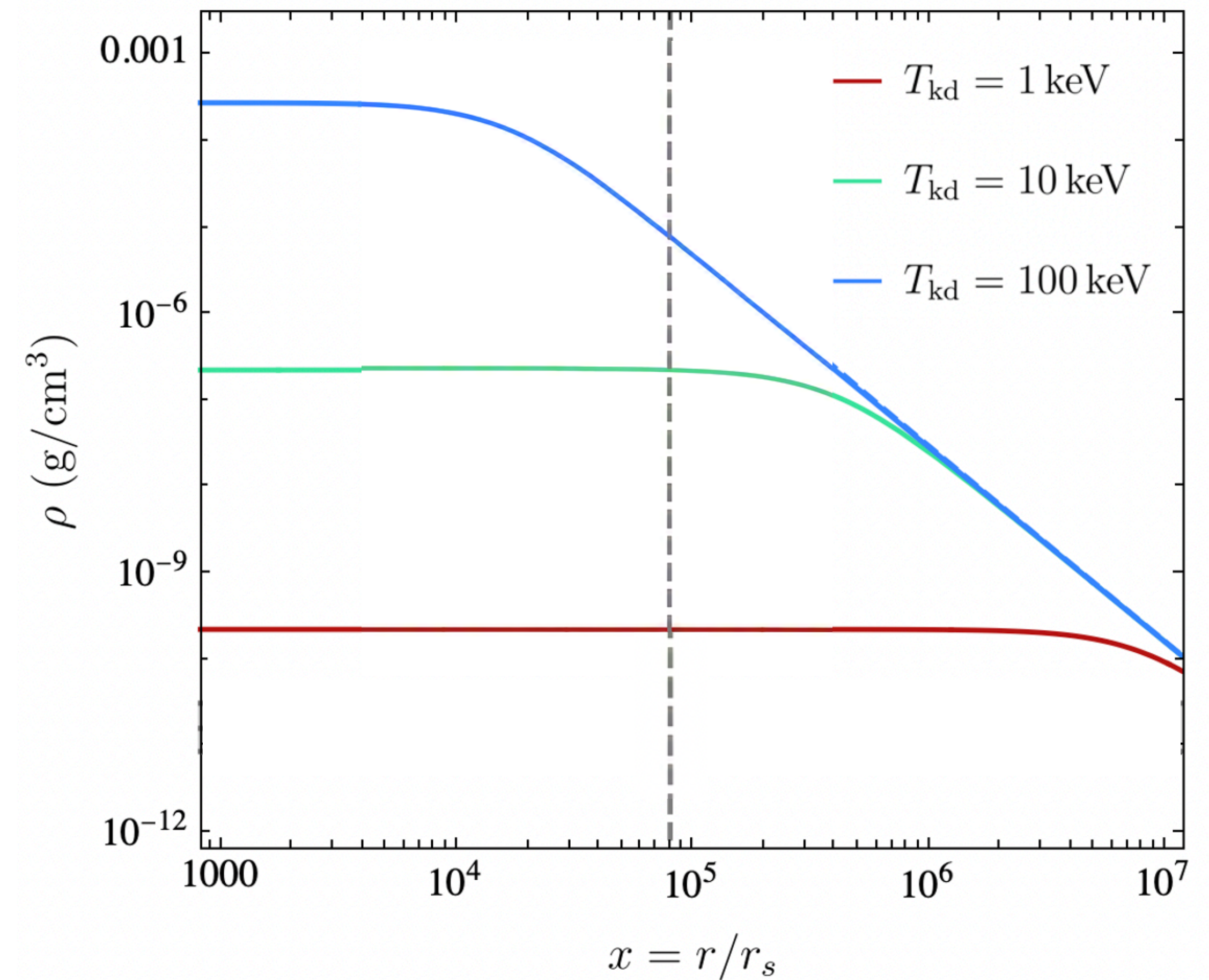
$$1 M_{\odot}/\text{pc}^3 \approx 10^{-22} \text{ g/cm}^3$$

$$\rho_{\text{DM, local}} \sim 10^{-2} M_{\odot}/\text{pc}^3$$

Self-Annihilation?

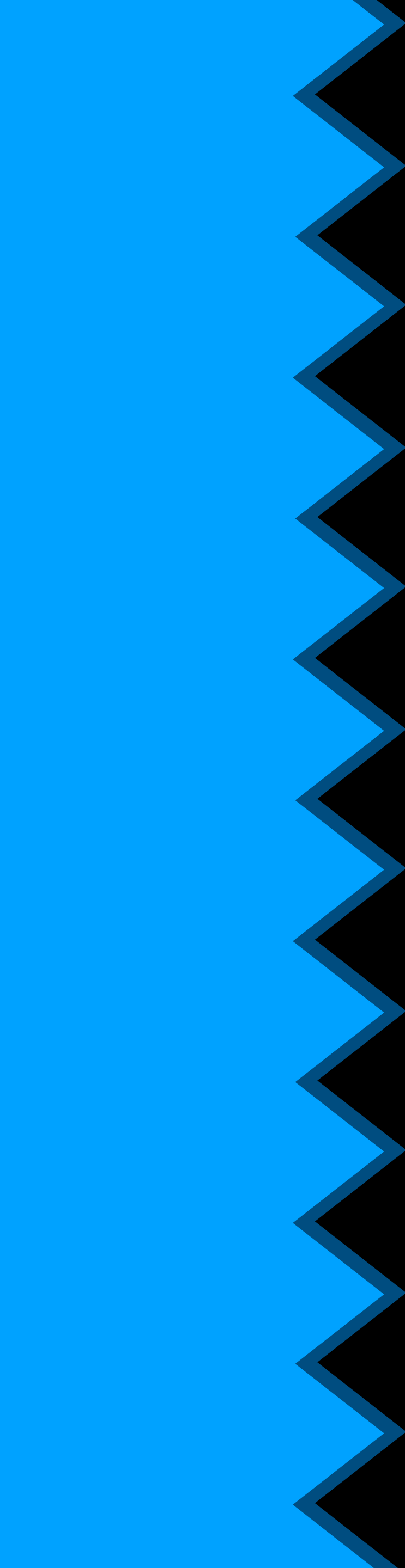


Kinetic Decoupling?



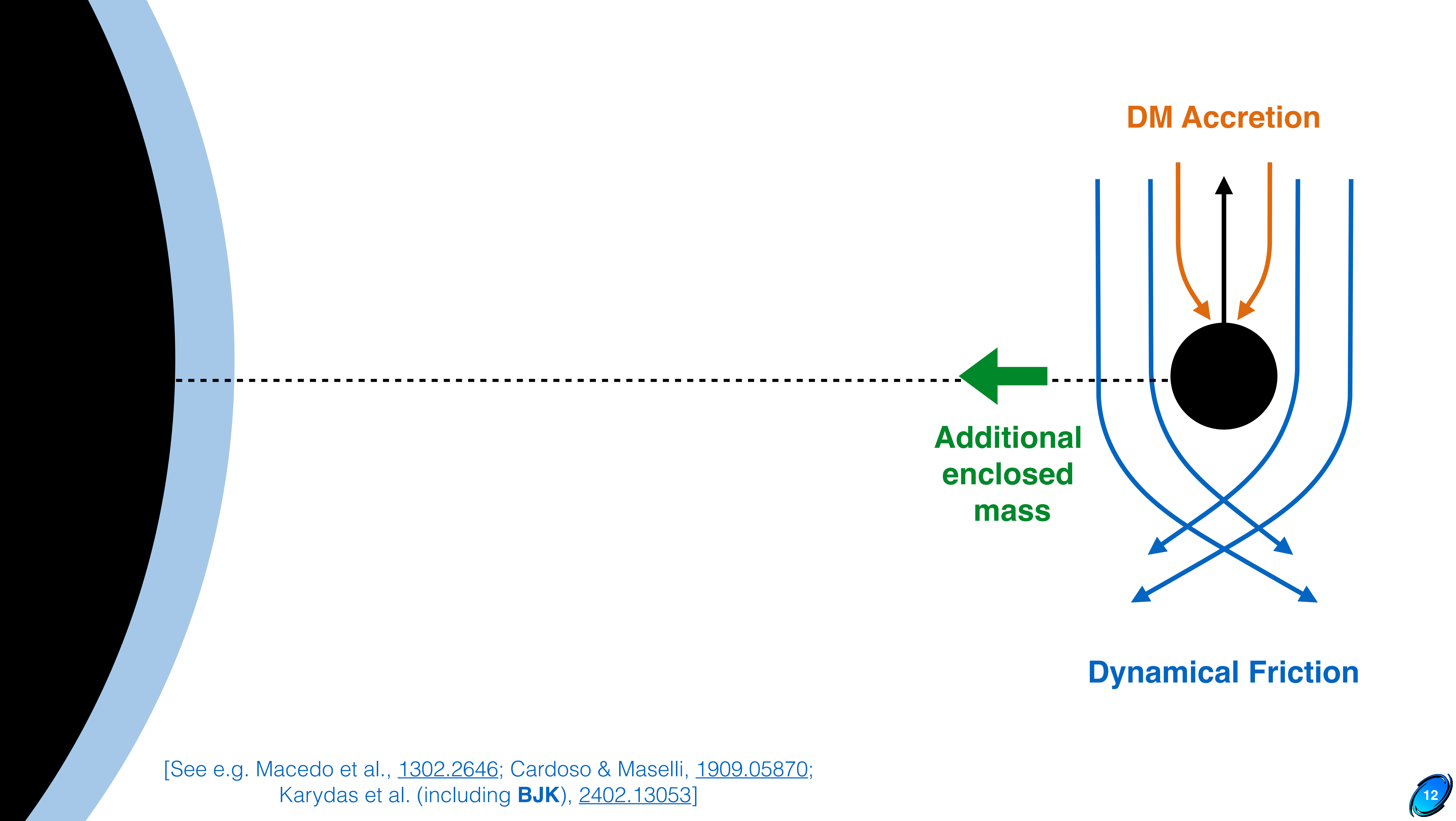
[e.g. Bertone et al. (including **BJK**), [1905.01238](#),
Lacki & Beacom, [1003.3466](#), Carr et al., [2011.01930](#)]

[Ireland, [2406.07624](#)]
[Eroshenko, [1607.00612](#)]

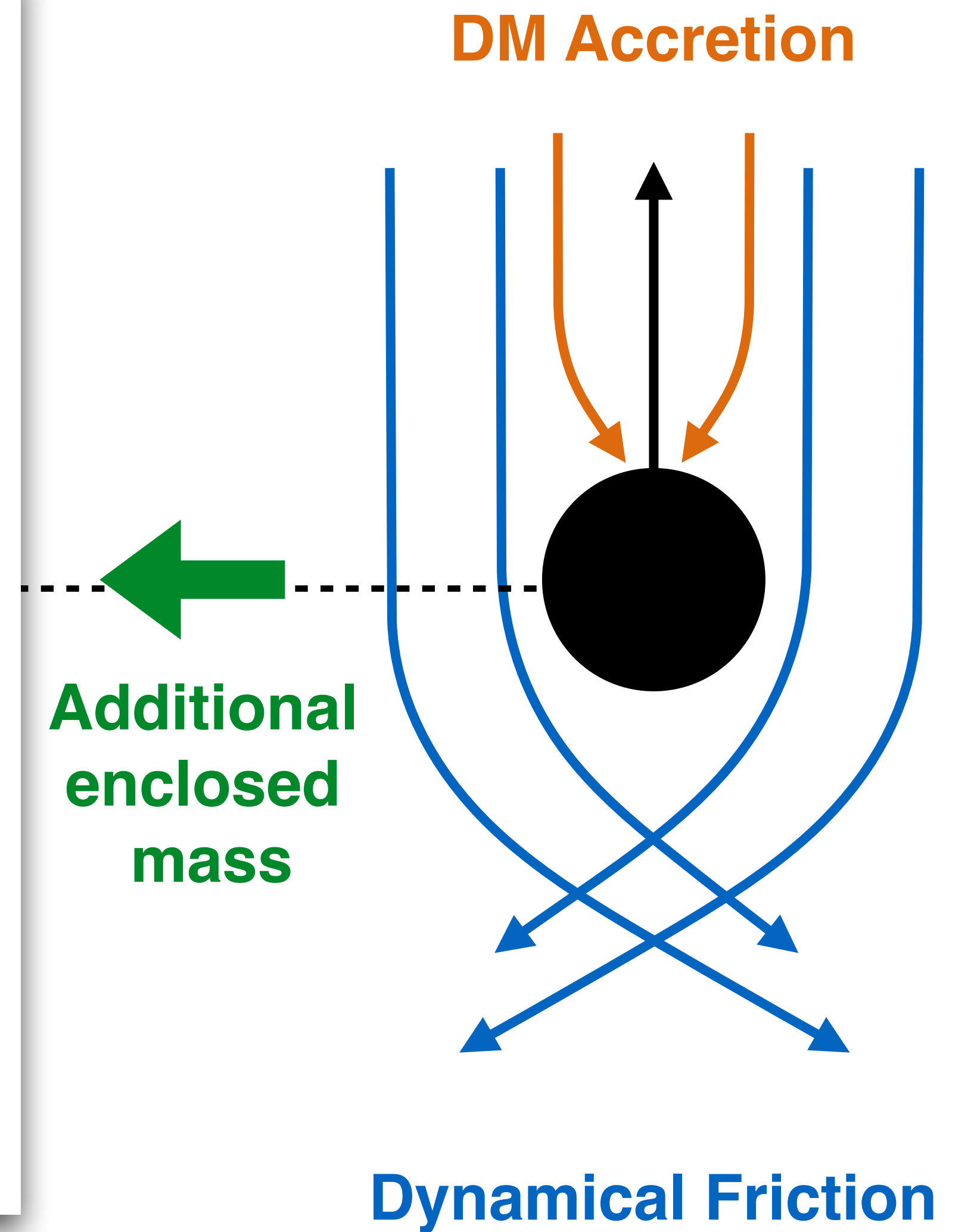
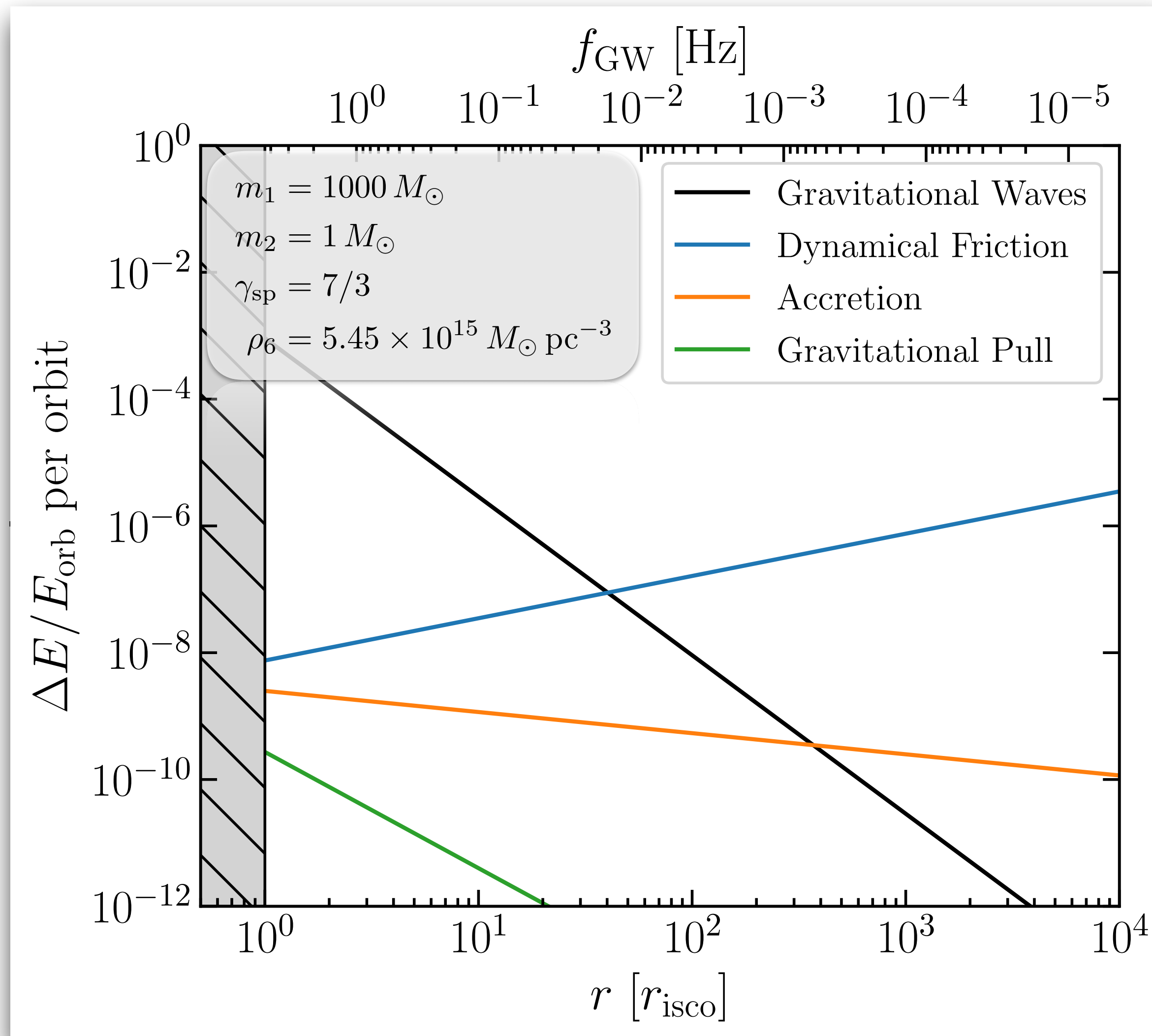


Gravitational Waves

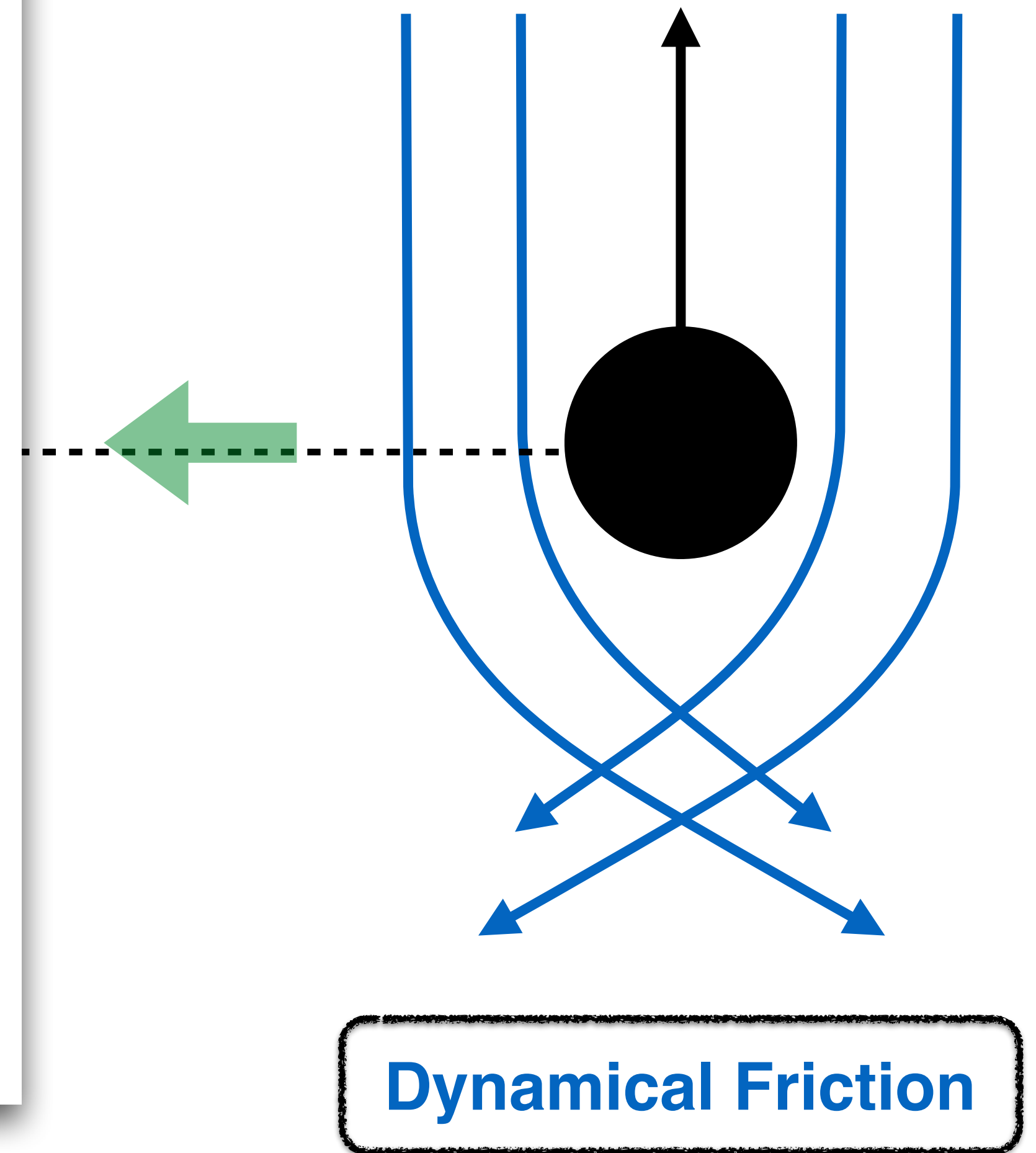
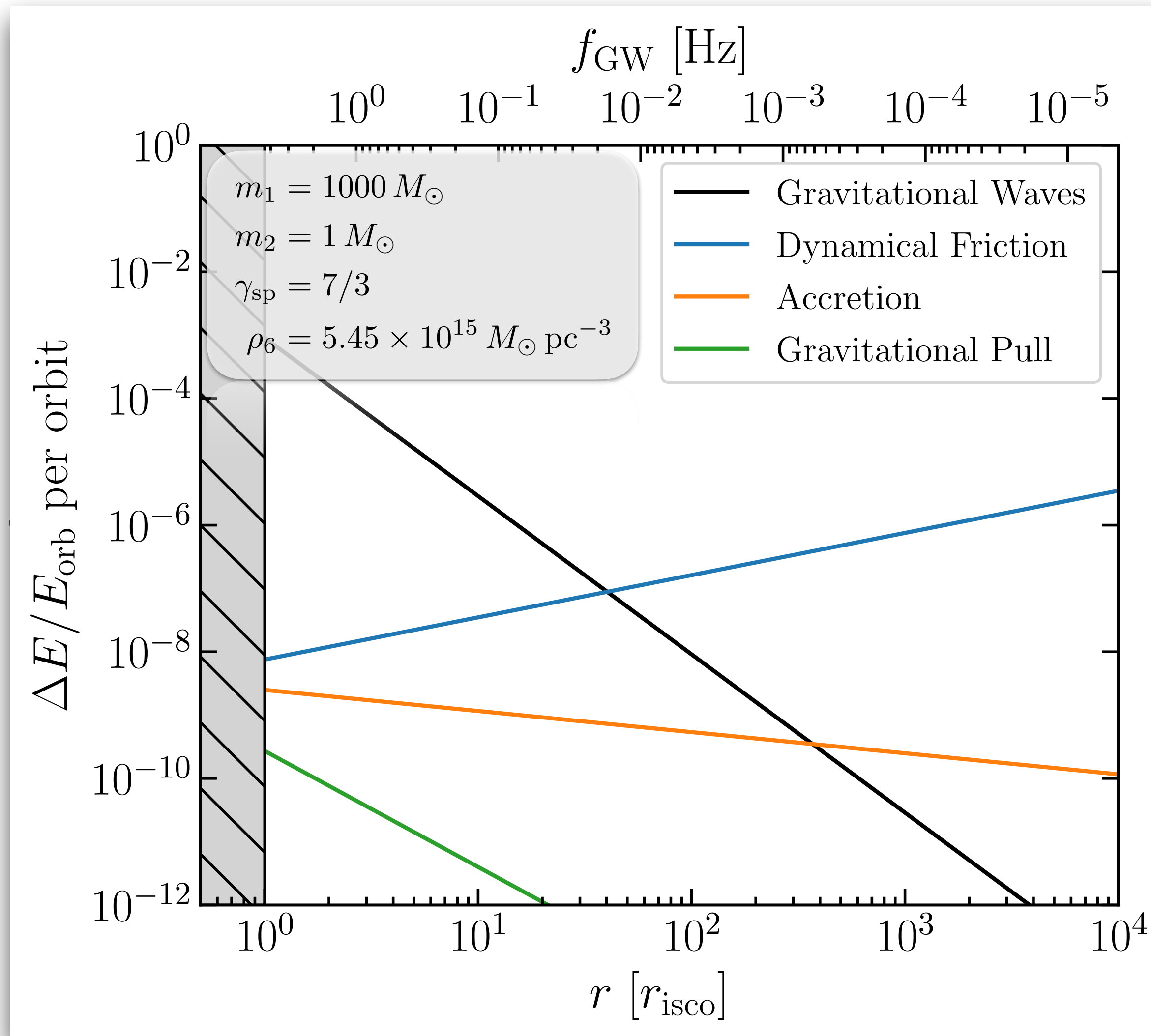
In collaboration with
Gianfranco Bertone, Theophanes Karydas, Francesca Scarcella,
Pippa Cole, Roberto Caiozzo, Adam Coogan, Daniele Gaggero, ...



[See e.g. Macedo et al., [1302.2646](#); Cardoso & Maselli, [1909.05870](#);
Karydas et al. (including **BJK**), [2402.13053](#)]



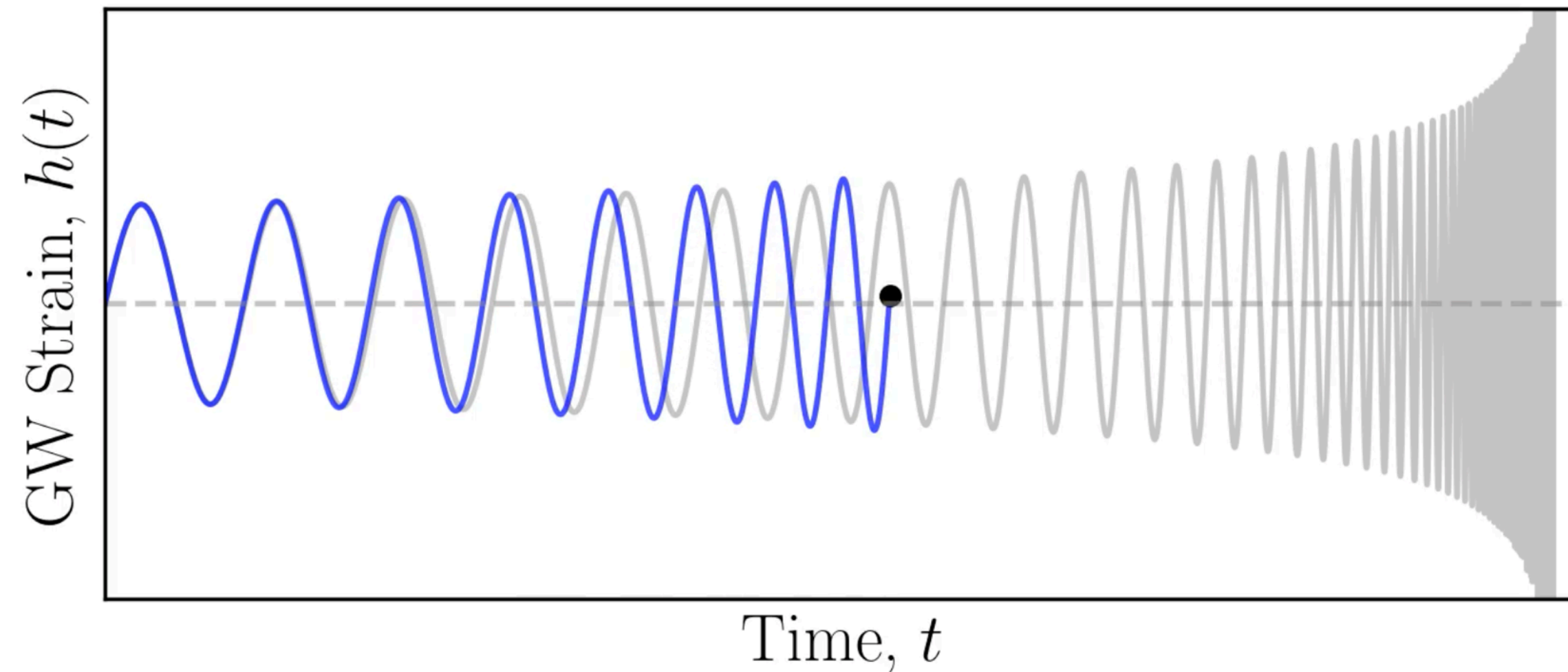
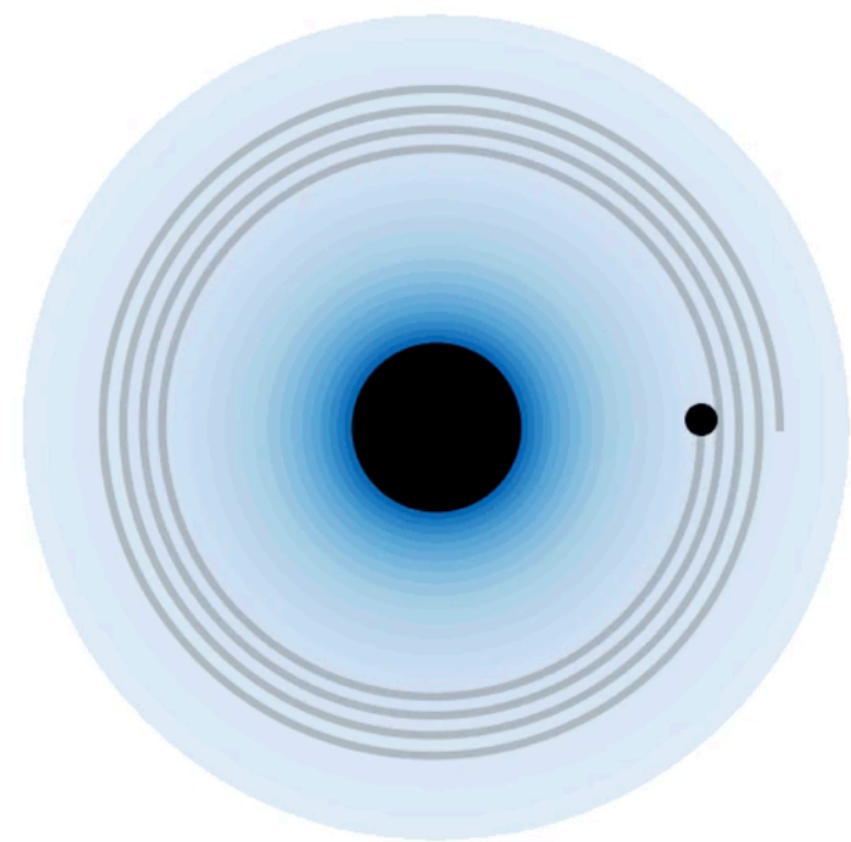
[See e.g. Macedo et al., [1302.2646](#); Cardoso & Maselli, [1909.05870](#);
 Karydas et al. (including **BJK**), [2402.13053](#)]



[See e.g. Macedo et al., [1302.2646](#); Cardoso & Maselli, [1909.05870](#);
 Karydas et al. (including **BJK**), [2402.13053](#)]

$$\dot{E}_{\text{DF}} \sim \frac{4\pi G^2 m_2^2 \rho_{\text{DM}}(r) \xi(v)}{v} \ln \Lambda$$

Gravitational Wave Inspiral



$$f_{\text{GW}} = 2f_{\text{orb}}$$

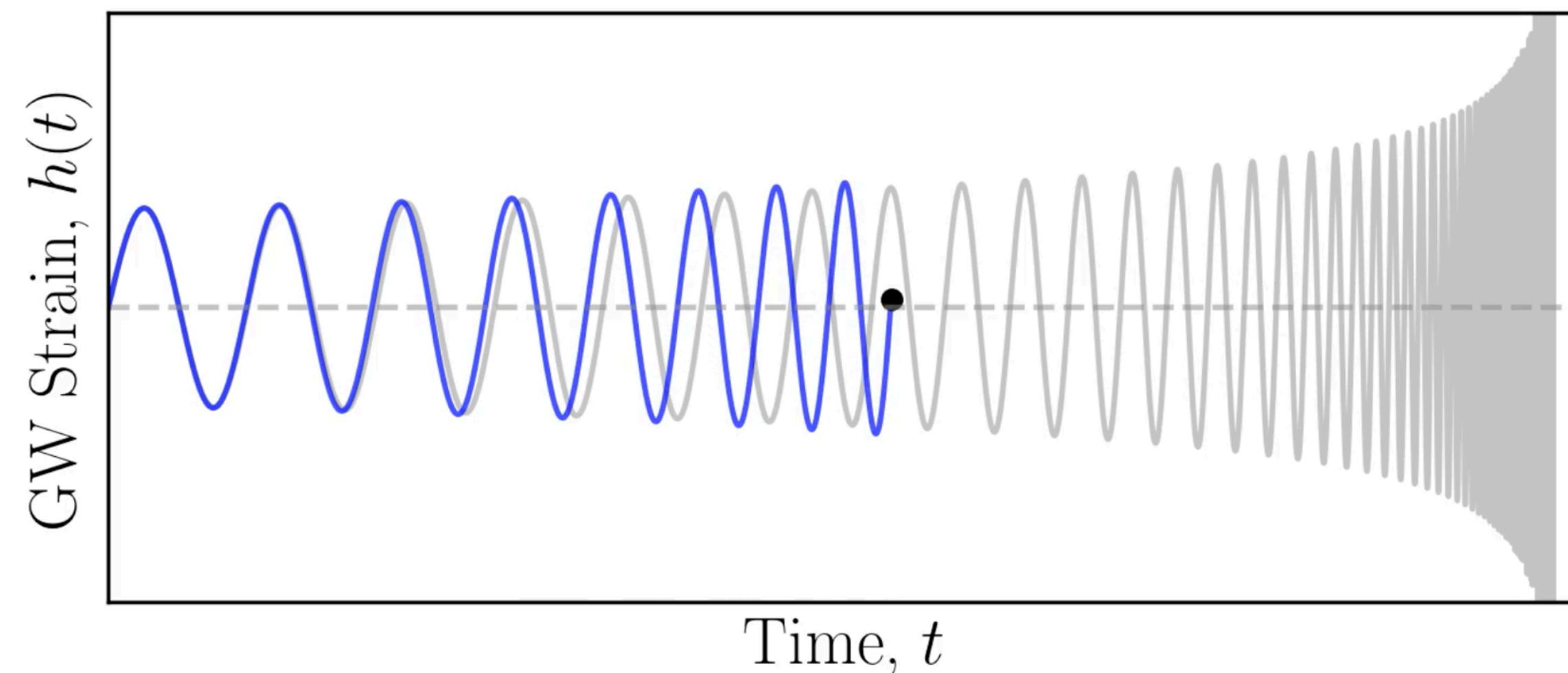
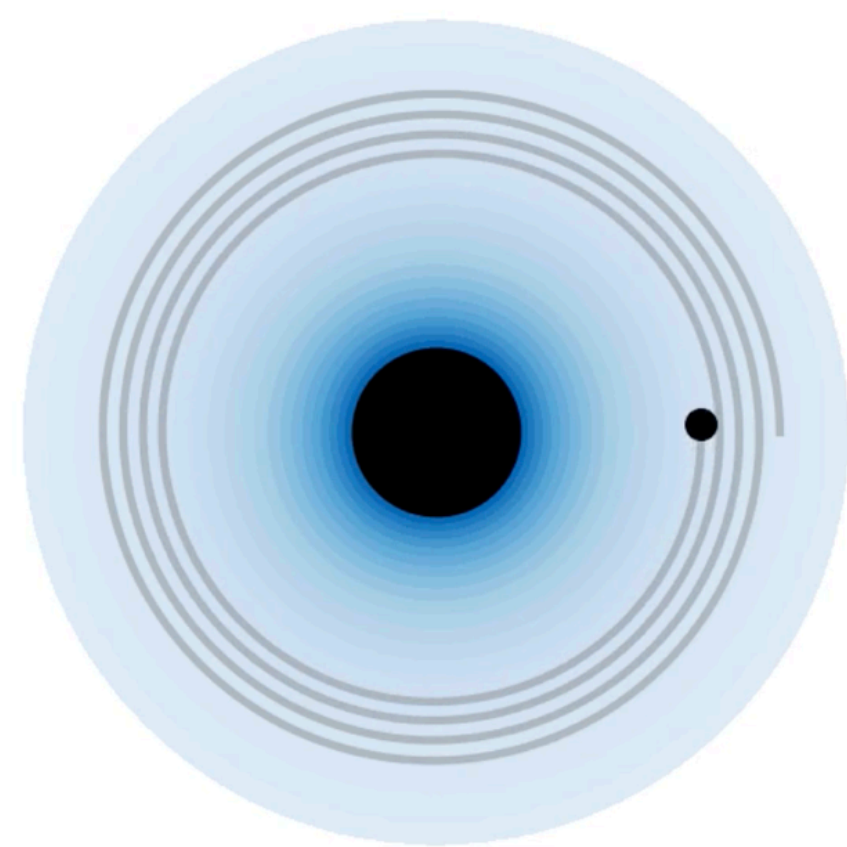
Evolution of the GW strain $h(t)$ and frequency $f_{\text{GW}}(t)$ is driven by the evolution of the orbital radius $r(t)$

Assuming quasi-circular orbit, we can relate the radius to the orbital energy: $E_{\text{orb}} = -Gm_1m_2/(2r)$

$$-\dot{E}_{\text{orb}} = \dot{E}_{\text{GW}} + \dot{E}_{\text{DF}}(\rho_{\text{DM}})$$

$$E_{\text{orb}}(t) \rightarrow r(t) \rightarrow f_{\text{GW}}(t)$$

Gravitational Wave Inspiral



$$f_{\text{GW}} = 2f_{\text{orb}}$$

Evolution of the GW strain $h(t)$ and frequency $f_{\text{GW}}(t)$ is driven by the evolution of the orbital radius $r(t)$

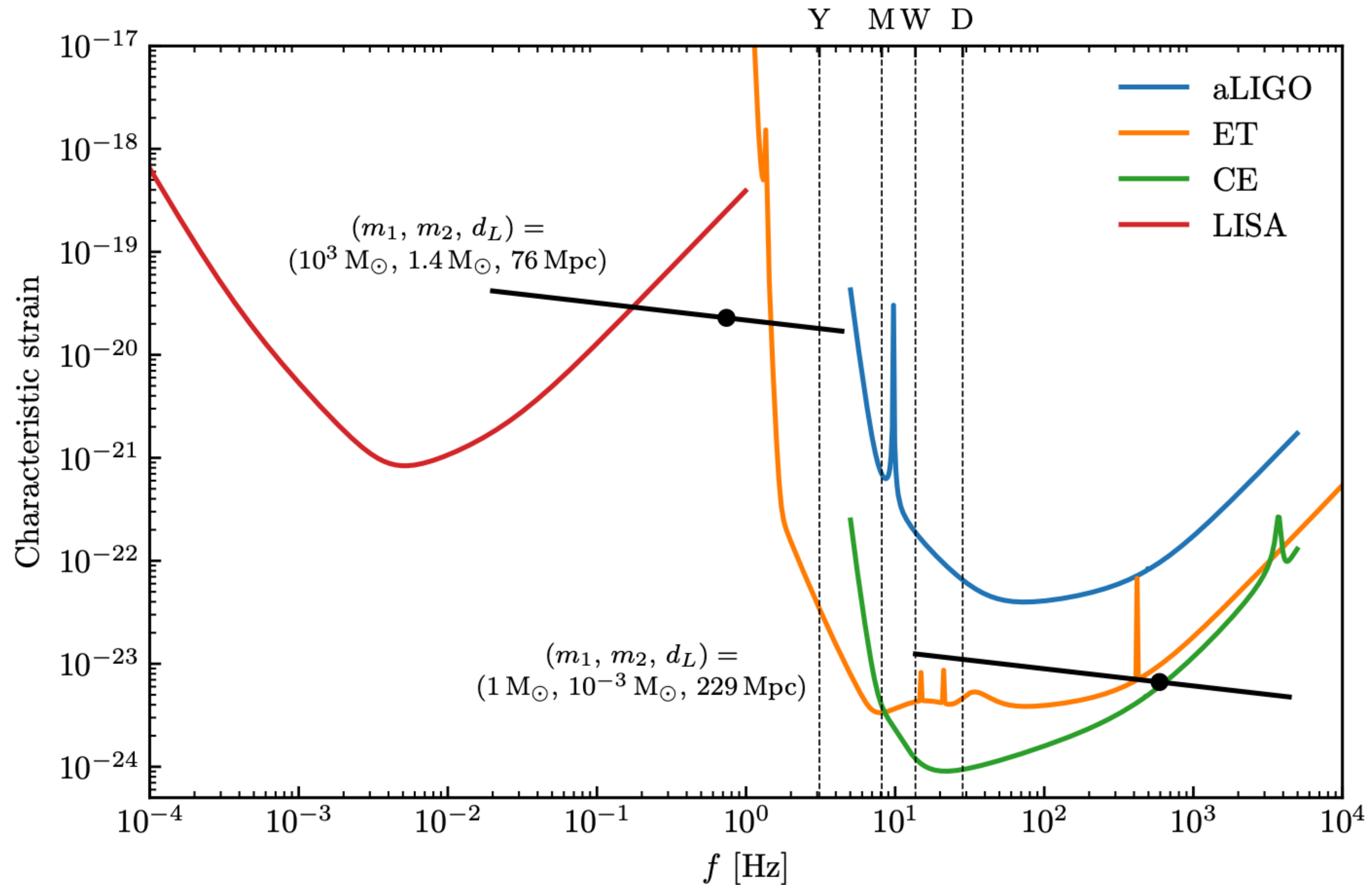
Assuming quasi-circular orbit, we can relate the radius to the orbital energy: $E_{\text{orb}} = -Gm_1m_2/(2r)$

$$-\dot{E}_{\text{orb}} = \dot{E}_{\text{GW}} + \dot{E}_{\text{DF}}(\rho_{\text{DM}})$$

$$E_{\text{orb}}(t) \rightarrow r(t) \rightarrow f_{\text{GW}}(t)$$

$$\dot{\rho}_{\text{DM}}(r) = \int \dot{f}_{\text{DM}}(\mathbf{r}, \mathbf{v}) d^3\mathbf{v}$$

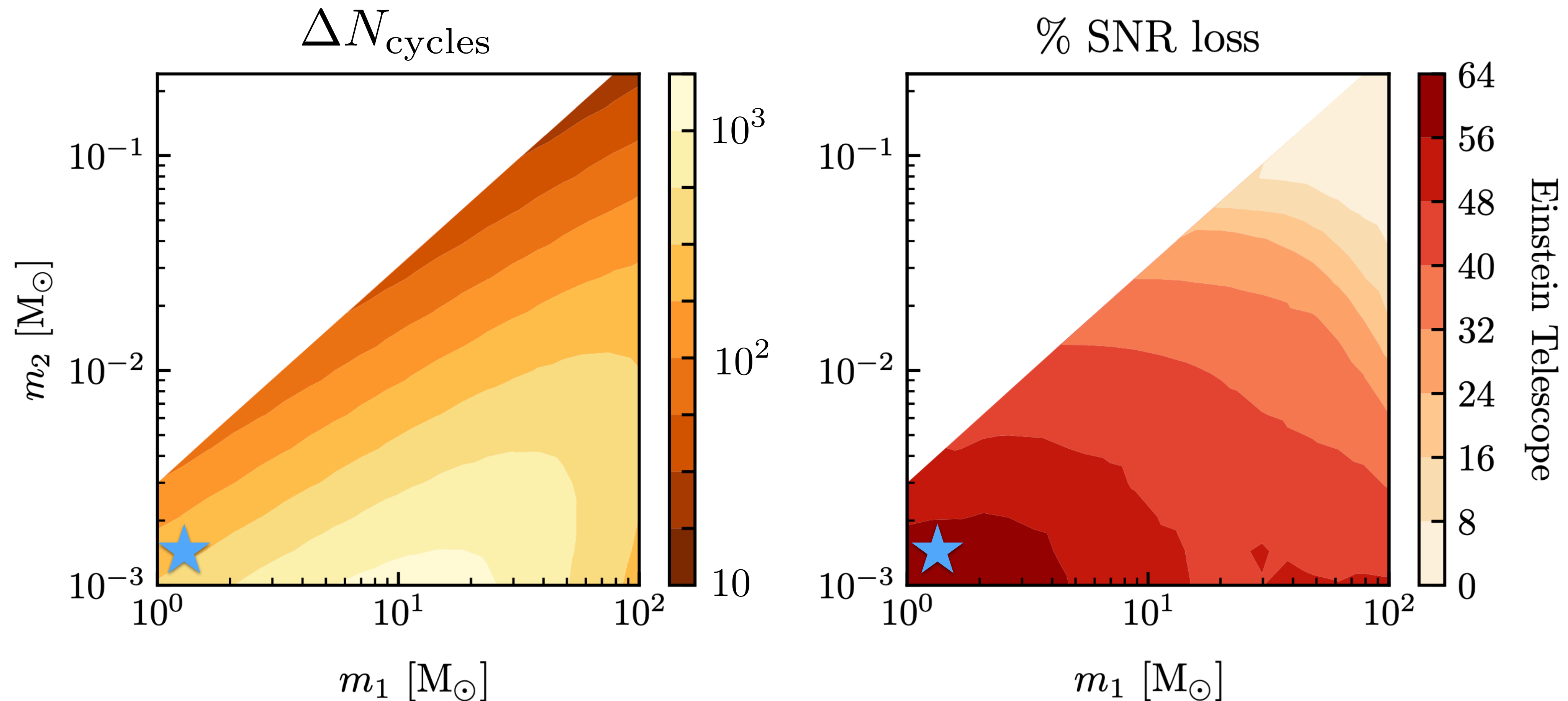
Feedback: Energy extracted from the binary is injected into the DM spike! This can substantially reduce the DM density and thus reduce the size of the dephasing effect.



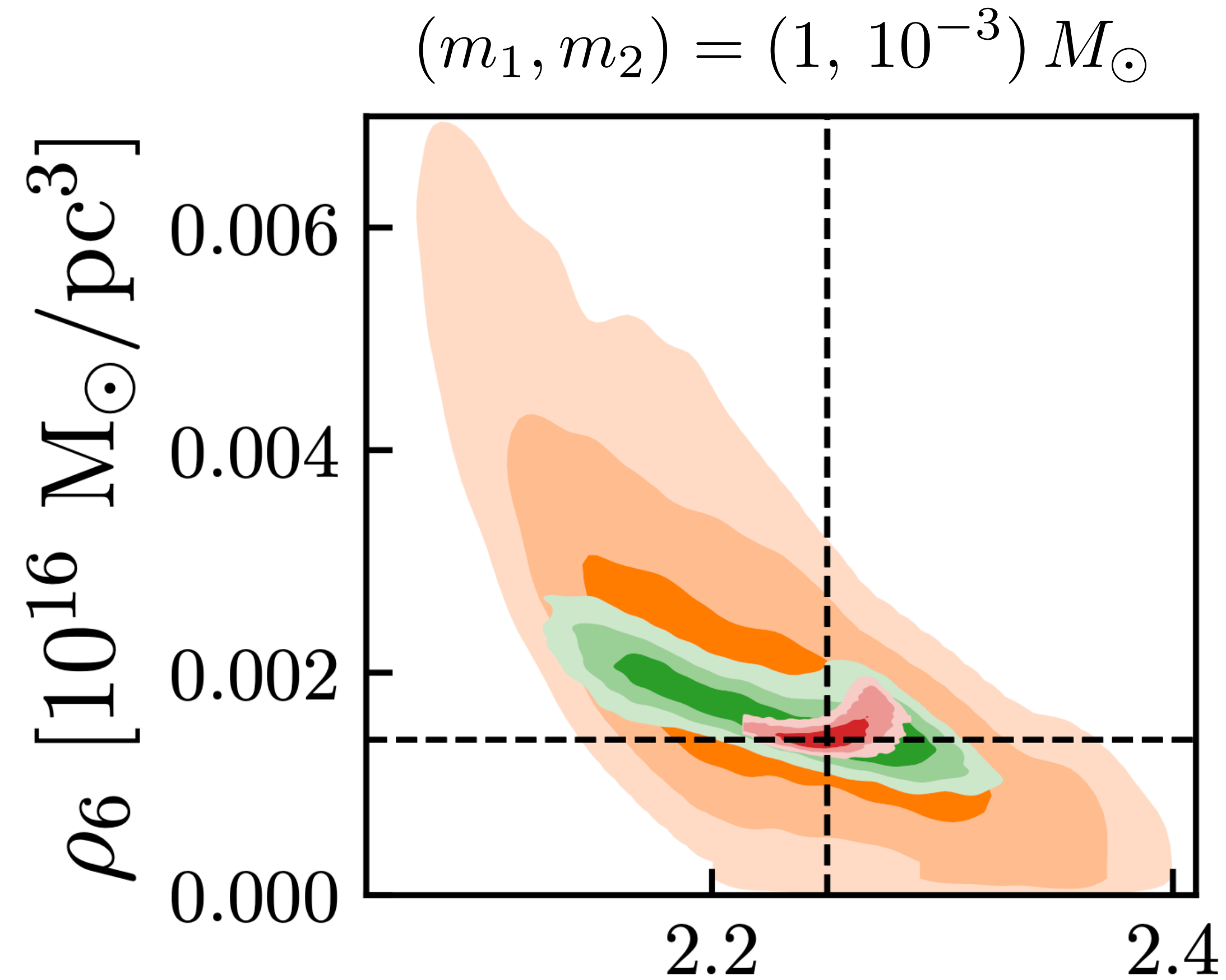
Consider now a binary of sub-solar mass PBHs,
observed with future ground-based detectors:

$$(m_1, m_2) = (1, 10^{-3}) M_{\odot}$$

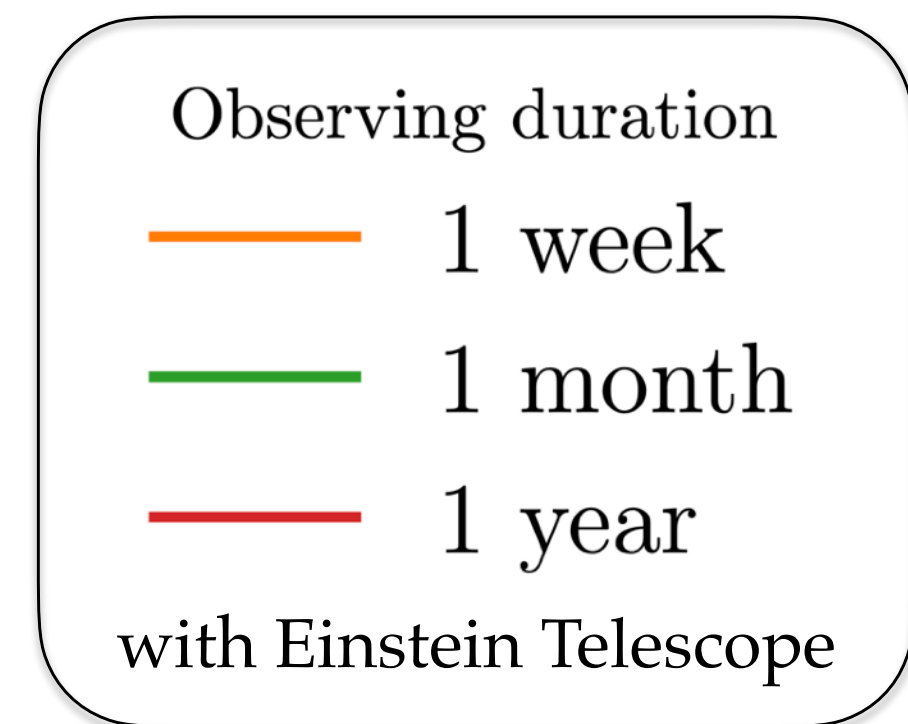
In vacuum, expect $\sim 10^7$ GW cycles during a one year observation. But with a DM spike:



Measuring the DM Spike



$$\rho_{\text{DM}}(r) = \rho_6 \left(\frac{r}{10^{-6} \text{ pc}} \right)^{-\gamma_{\text{sp}}}$$



Expect DM spike properties to be measurable with ~ 1 week of observation!

[Cole et al. (including **BJK**), [2207.07576](#)]

Distinguishable from other environmental effects (baryons, light bosonic fields, ...)!

[Cole et al. (including **BJK**), [2211.01362](#)]

Thinking about how to perform these searches for environmental effects with upcoming LVK + future detectors...

Hints in LMXBs?

In collaboration with
Francesca Scarcella

[arXiv:2510.11635](https://arxiv.org/abs/2510.11635)

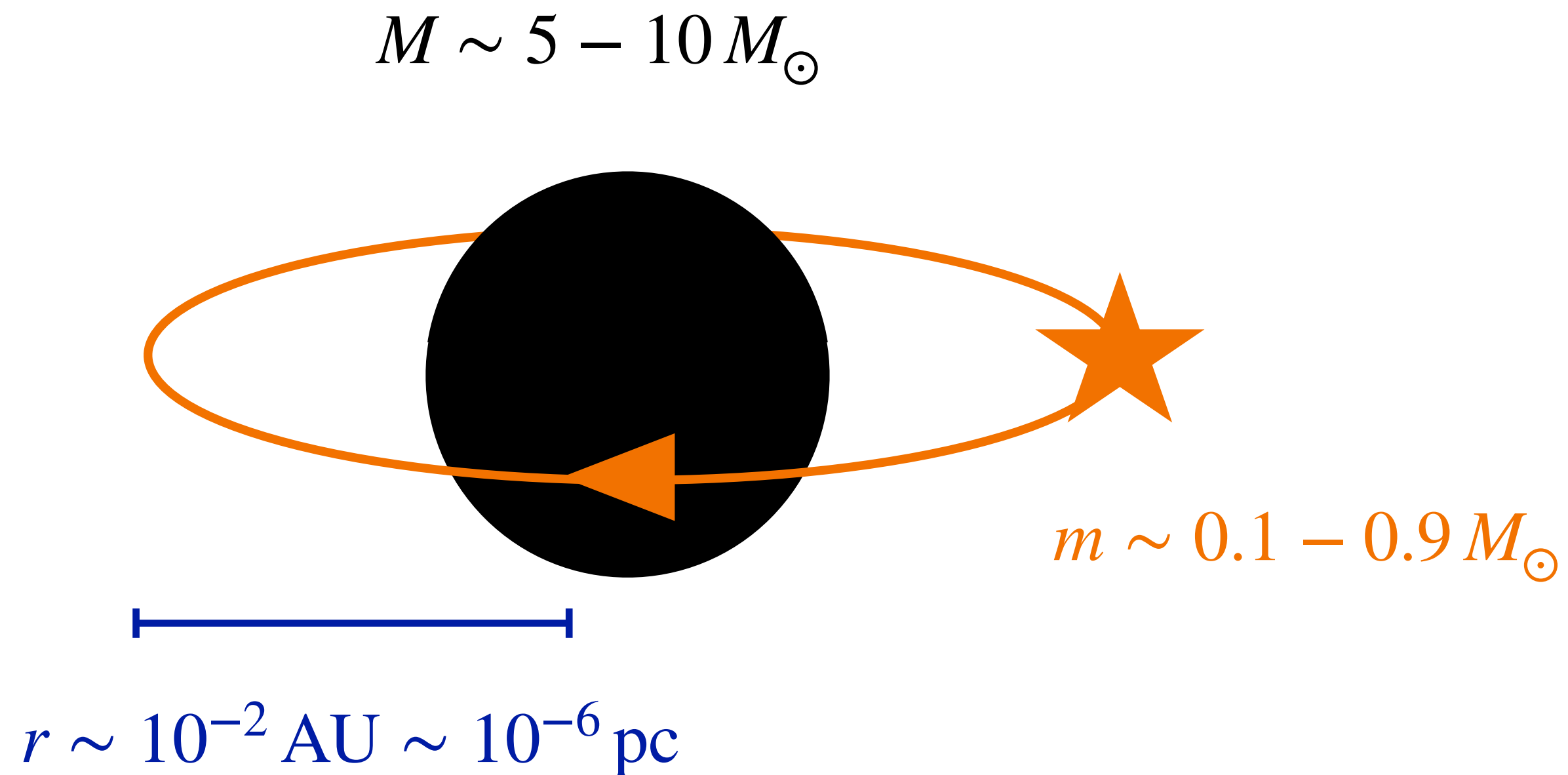


Low-mass Black-hole X-ray Binaries (LMXBs)

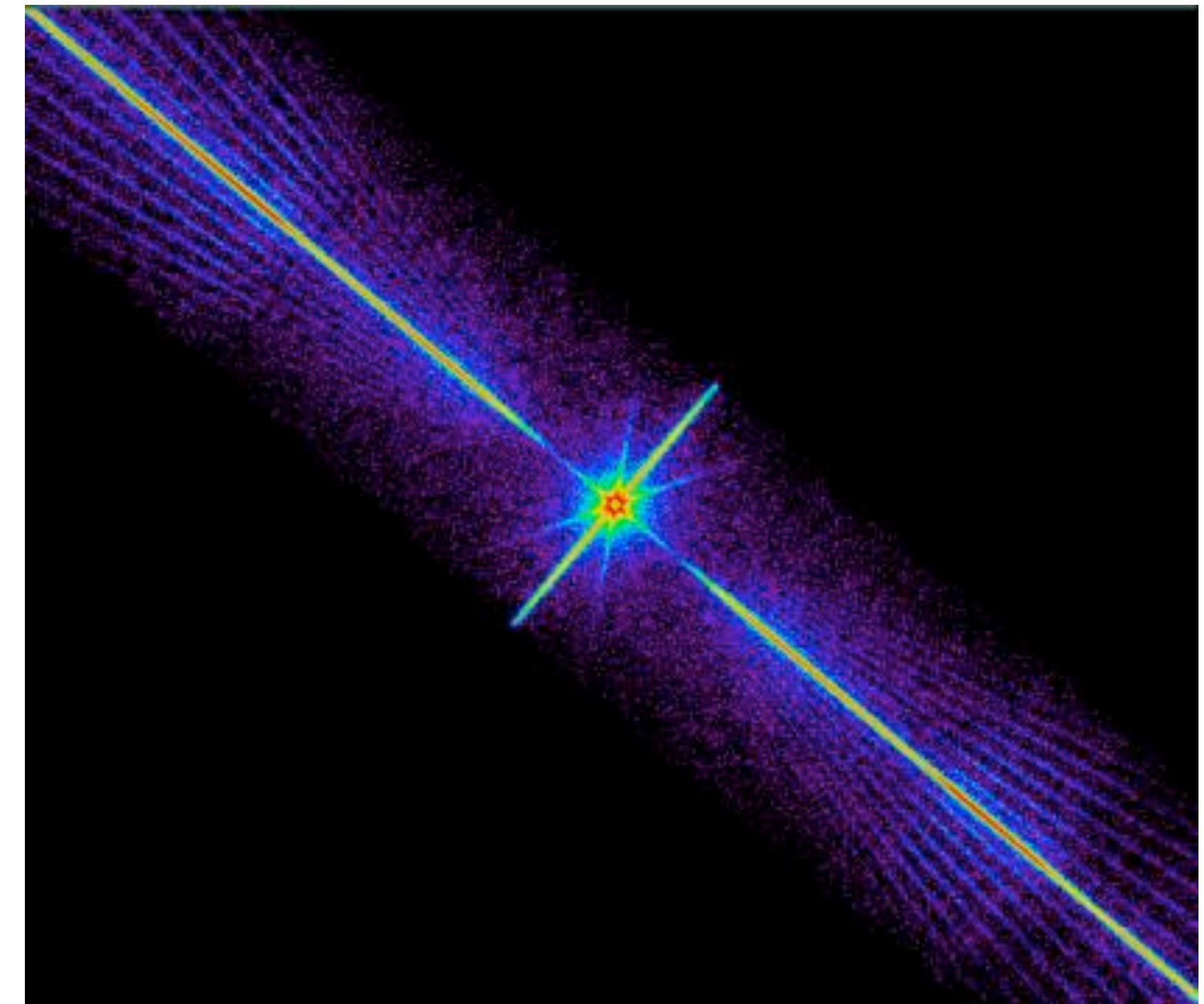
~ 20 observed

~ 1 kpc from Sun

Period $P \sim$ few hours



The period of LMXBs changes (very) slowly as they inspiral due to gravitational wave emission and other mechanisms such as mass transfer or magnetic braking.



Chandra Observations of XTE J1118+480
[McClintock et al., [astro-ph/0103051](https://arxiv.org/abs/astro-ph/0103051)]

Three LMXBs have measured period decay rates, $\dot{P} \rightarrow$ all three anomalously large!

[González Hernández et al., [1311.5412](#), [1609.02961](#), van Grunsven et al., [1708.08209](#)]

	System A	System B	System C
	XTE J1118+480	A0620-00	NM1991
$M_{\text{BH}} [M_{\odot}]$	$7.46^{+0.34}_{-0.69}$ [46]	5.86 ± 0.24 [59]	$11.0^{+2.1}_{-1.4}$ [47]
$M_{\star} [M_{\odot}]$	0.18 ± 0.06 [46]	0.40 ± 0.01 [46]	0.89 ± 0.18 [47]
$r_{\star} [R_{\odot}]$	0.34 ± 0.05 [47]	0.67 ± 0.02 [47]	1.06 ± 0.07 [47]
$q = M_{\star}/M_{\text{BH}}$	0.024 ± 0.009 [46]	0.060 ± 0.004 [59]	0.079 ± 0.007 [47]
$r_{\text{orb}} [R_{\odot}]$	2.54 ± 0.06	3.79 ± 0.04	5.49 ± 0.32
P_0 [day]	$0.16993404(5)$ [46]	$0.32301415(7)$ [46]	$0.432605(1)$ [47]
$\dot{P}$ [ms/yr]	-1.90 ± 0.57 [46]	-0.60 ± 0.08 [46]	-20.7 ± 12.7 [47]

~10x larger than
expected!

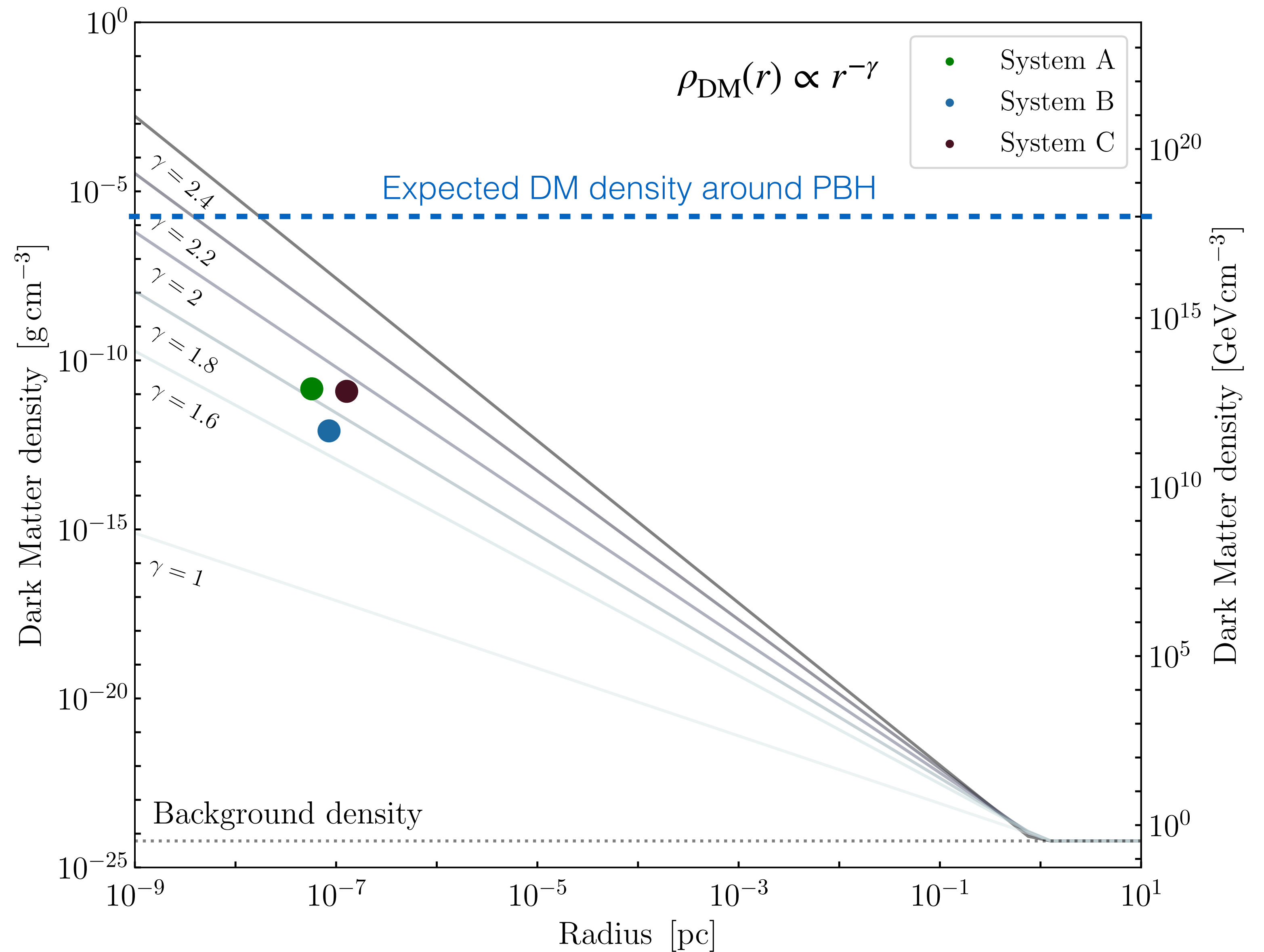
~10x larger than
expected!

~100x larger than
expected!

Constraints on the DM spike profile

(Naively?) interpret the anomalous $\dot{P}$ as arising from dynamical friction due to a DM spike:

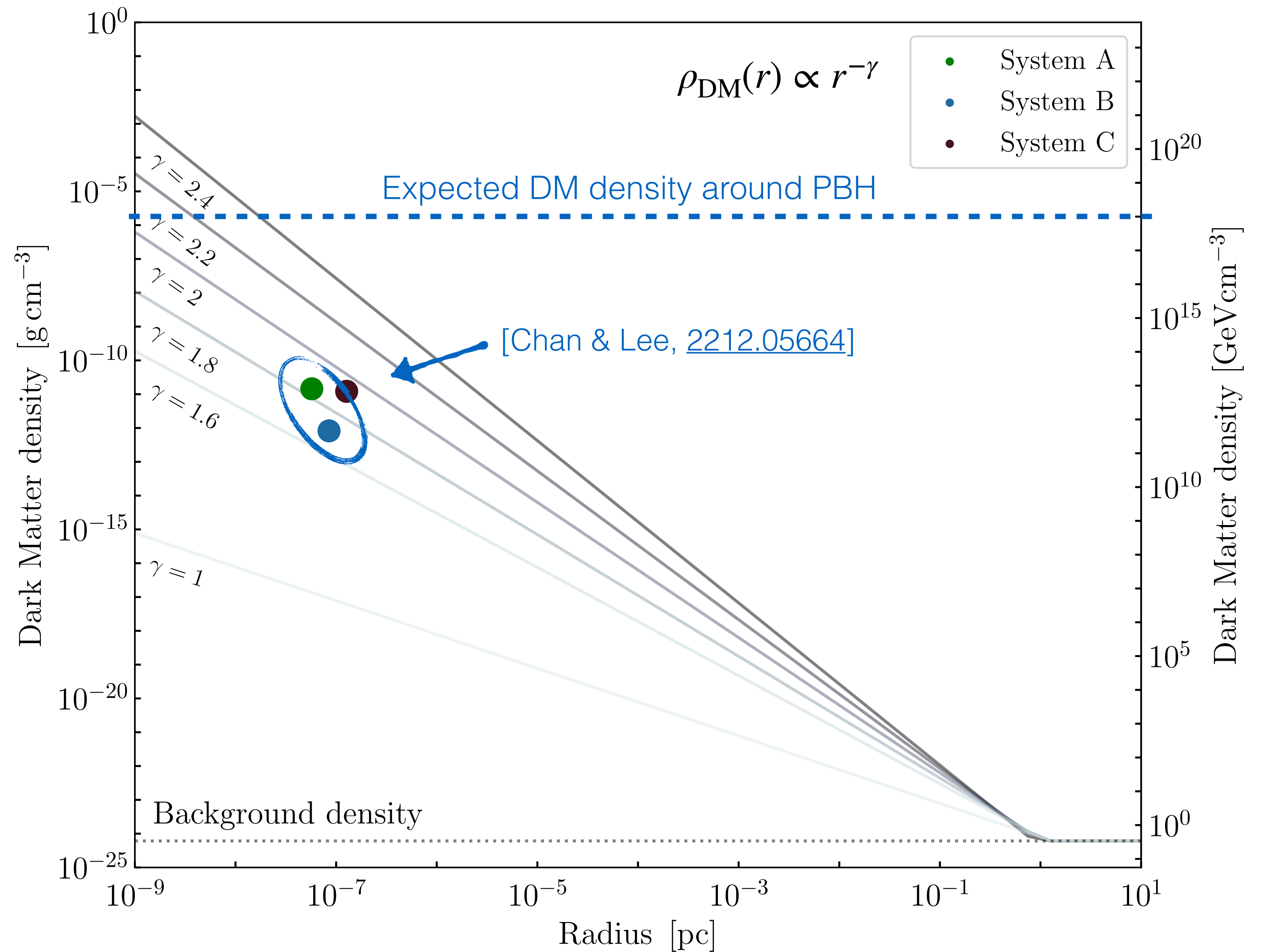
$$\dot{P} \propto -\frac{M_{\star}}{M_{\text{BH}}} P^2 \rho_{\text{DM}}$$



Constraints on the DM spike profile

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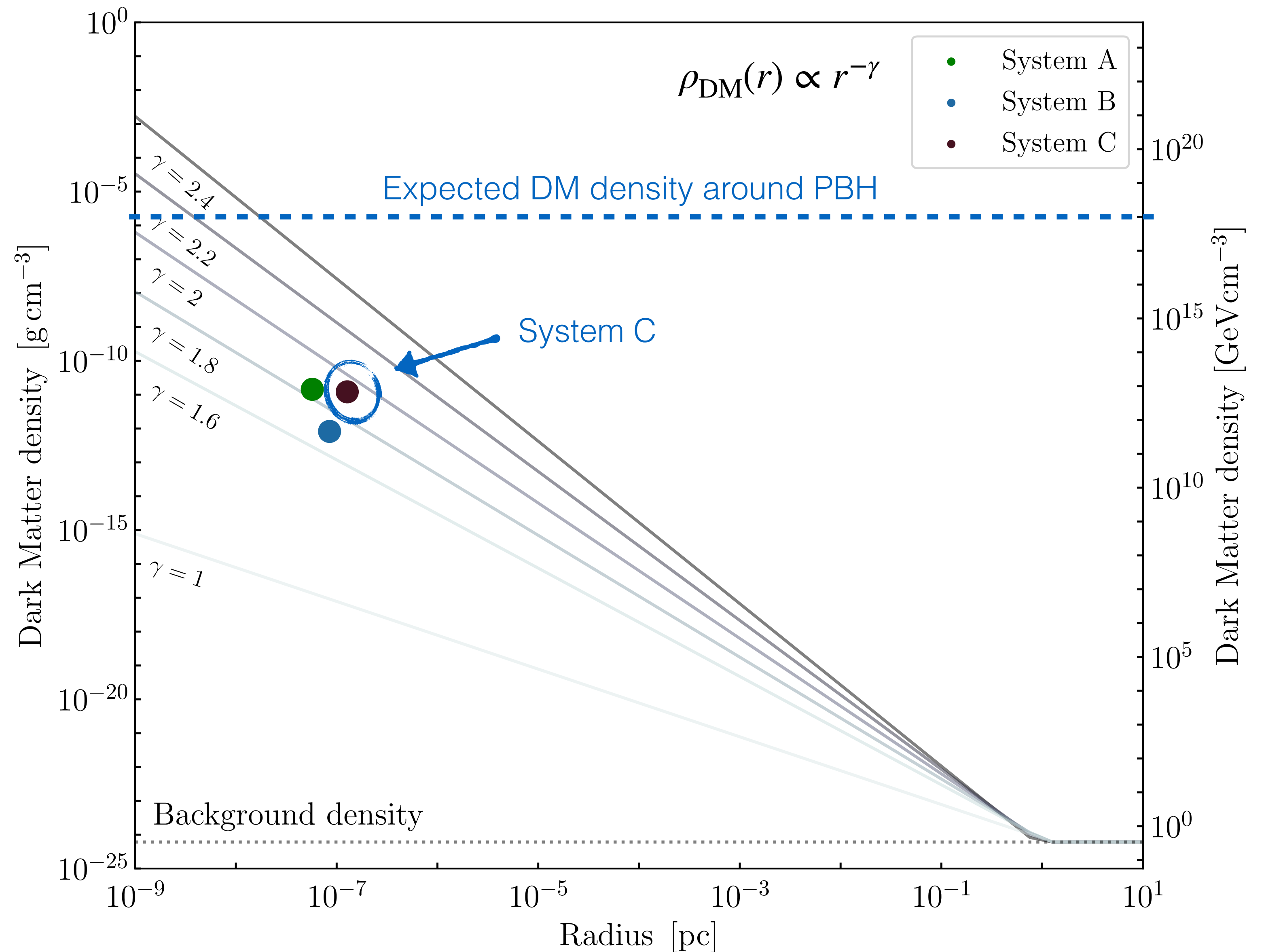
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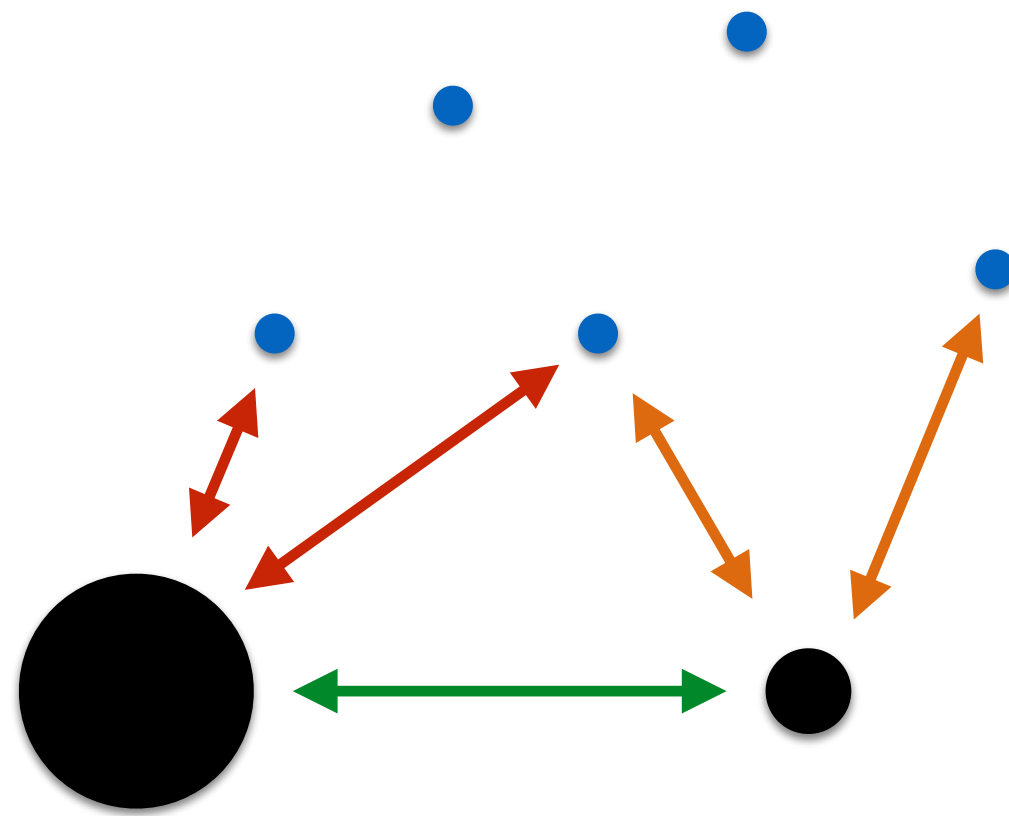


Simulations with NbodyIMRI

[Scarcella & **BJK**, [2510.11635](#)]

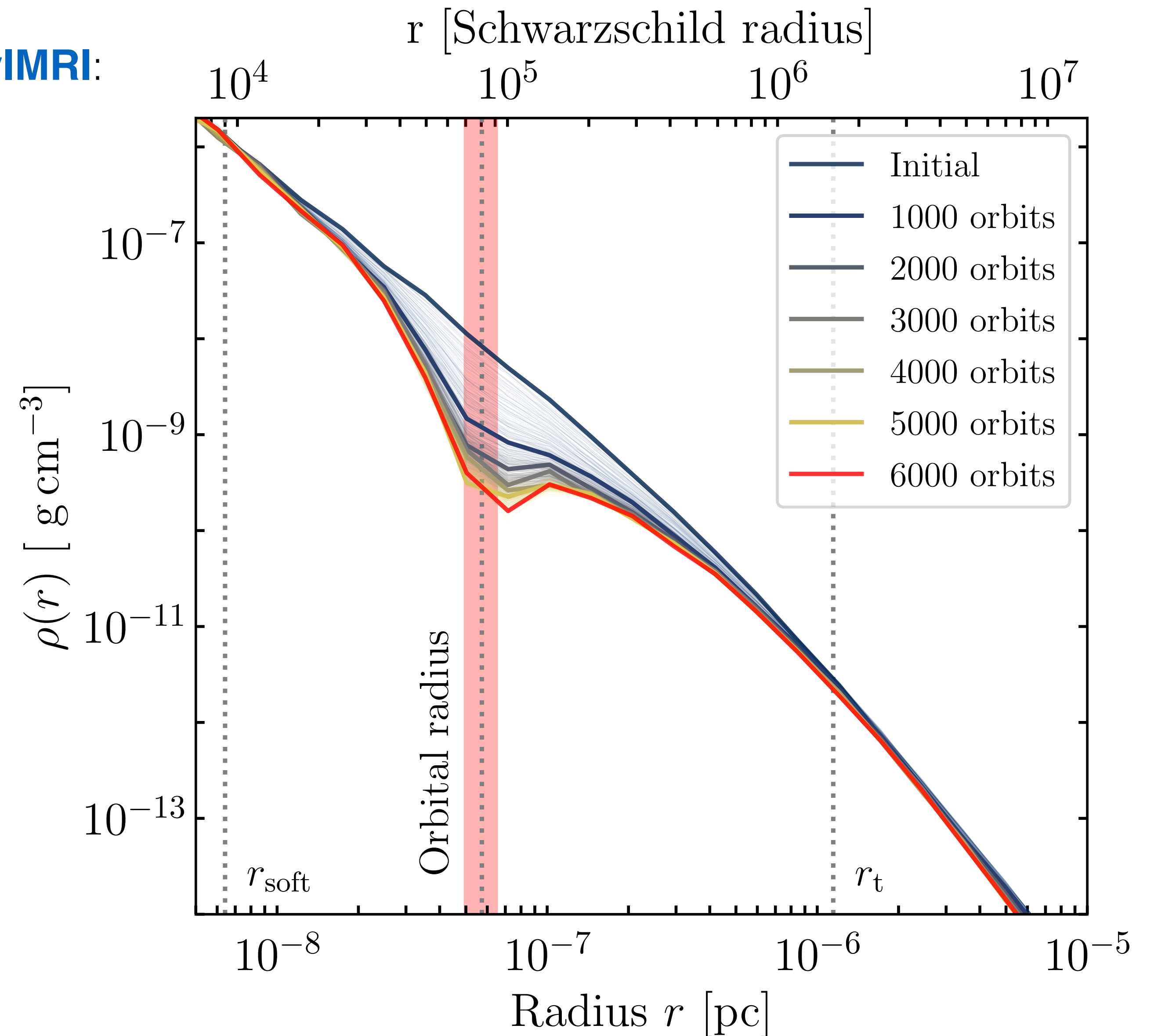
Simulate each of the 3 LMXB systems with **NbodyIMRI**:

Newtonian N-body solver tailored to DM spikes.



Neglect GW emission and *ignore DM-DM interparticle forces*.

Focus on understanding co-evolution of spike and binary.



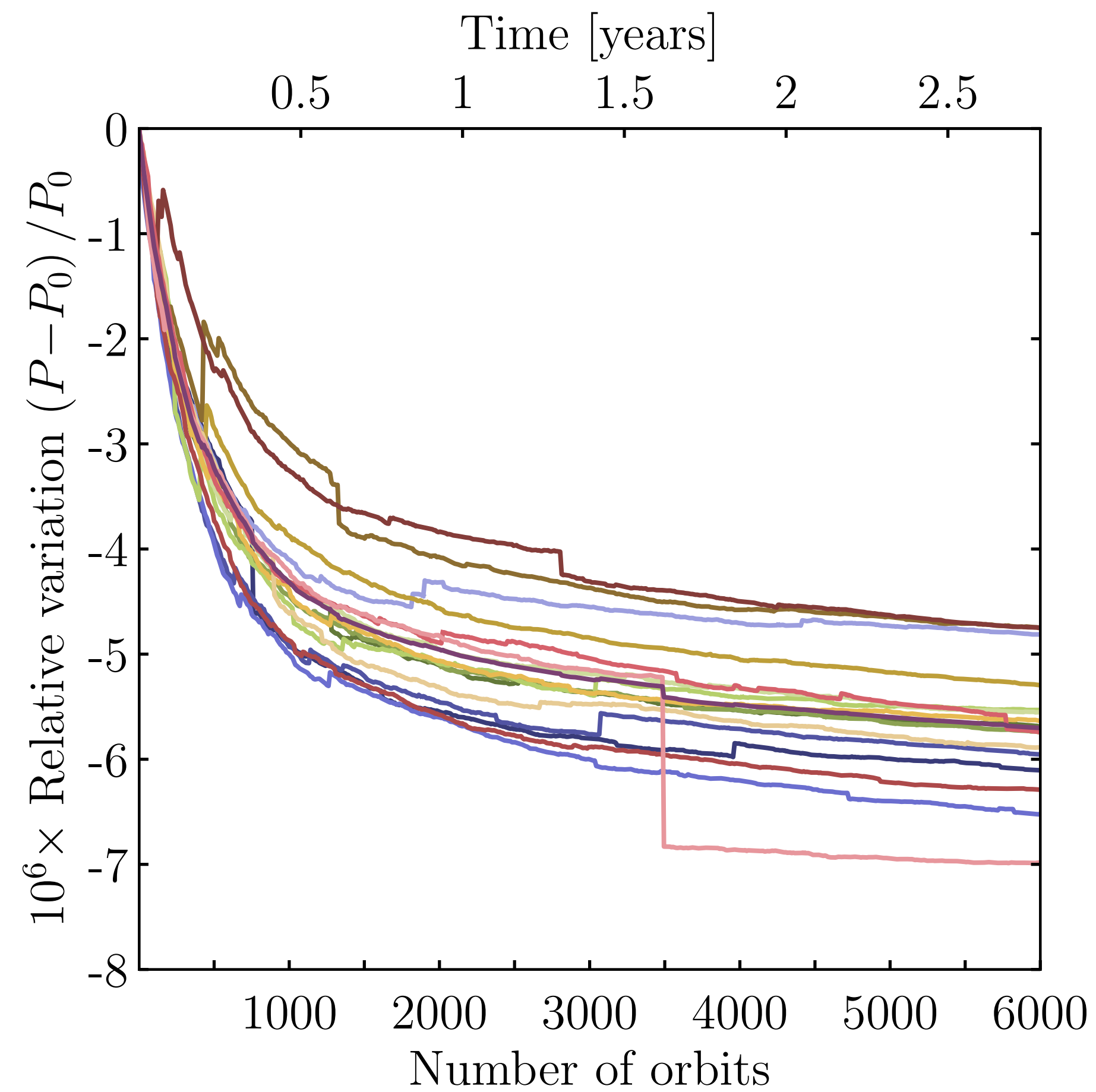
[**BJK** et al., [2402.13762](#)]

[Code here: github.com/bradkav/NbodyIMRI]

Estimating the rate of decay $\dot{P}(\gamma)$

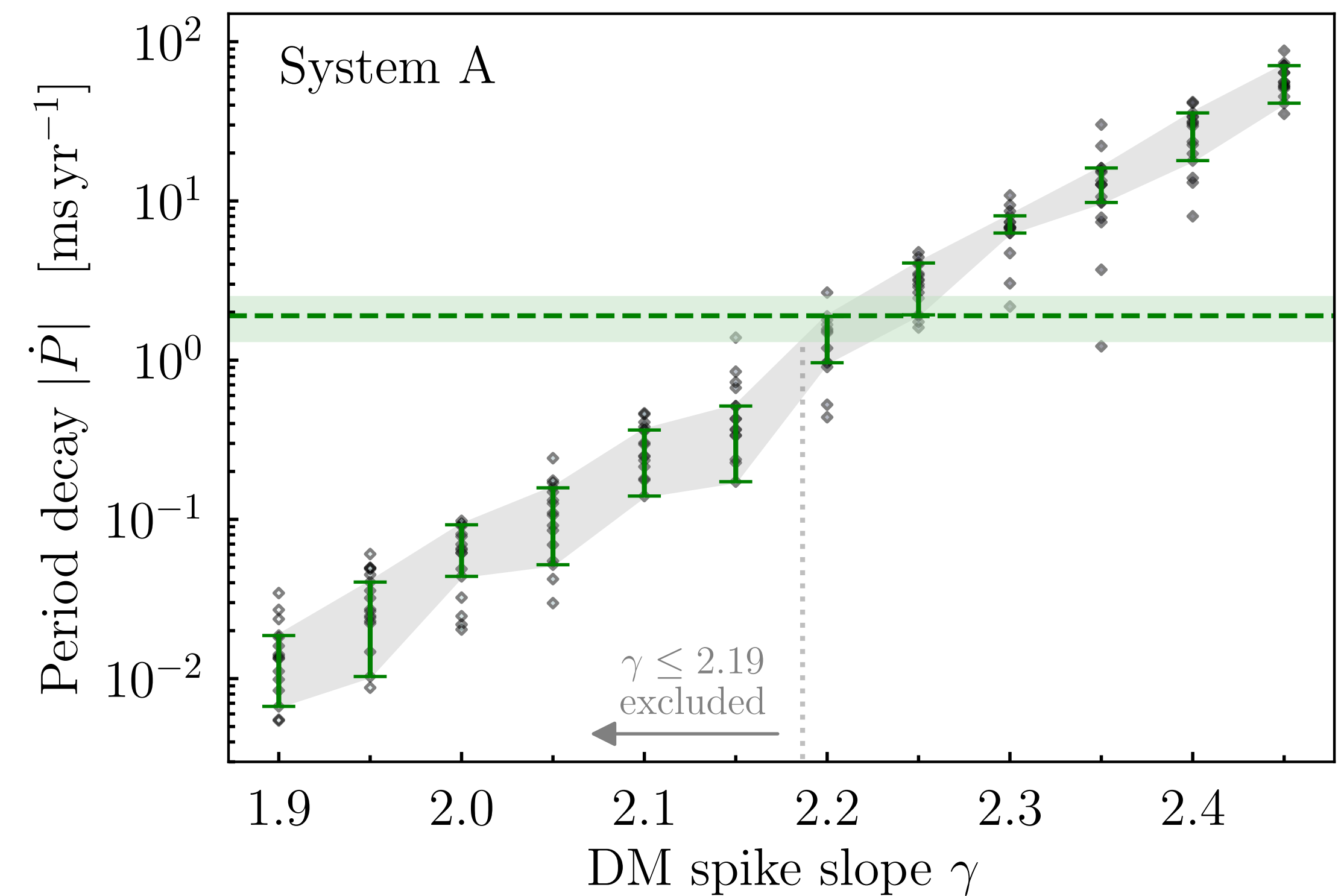
[Scarcella & **BJK**, [2510.11635](#)]

Decay of the orbital period slows with time due to depletion of the spike:



Estimate derivative $\dot{P} = \langle \Delta P / \Delta t \rangle_{1000 \text{ orbits}}$

Collect final values of from each realisation, for all values of $\dot{P}$



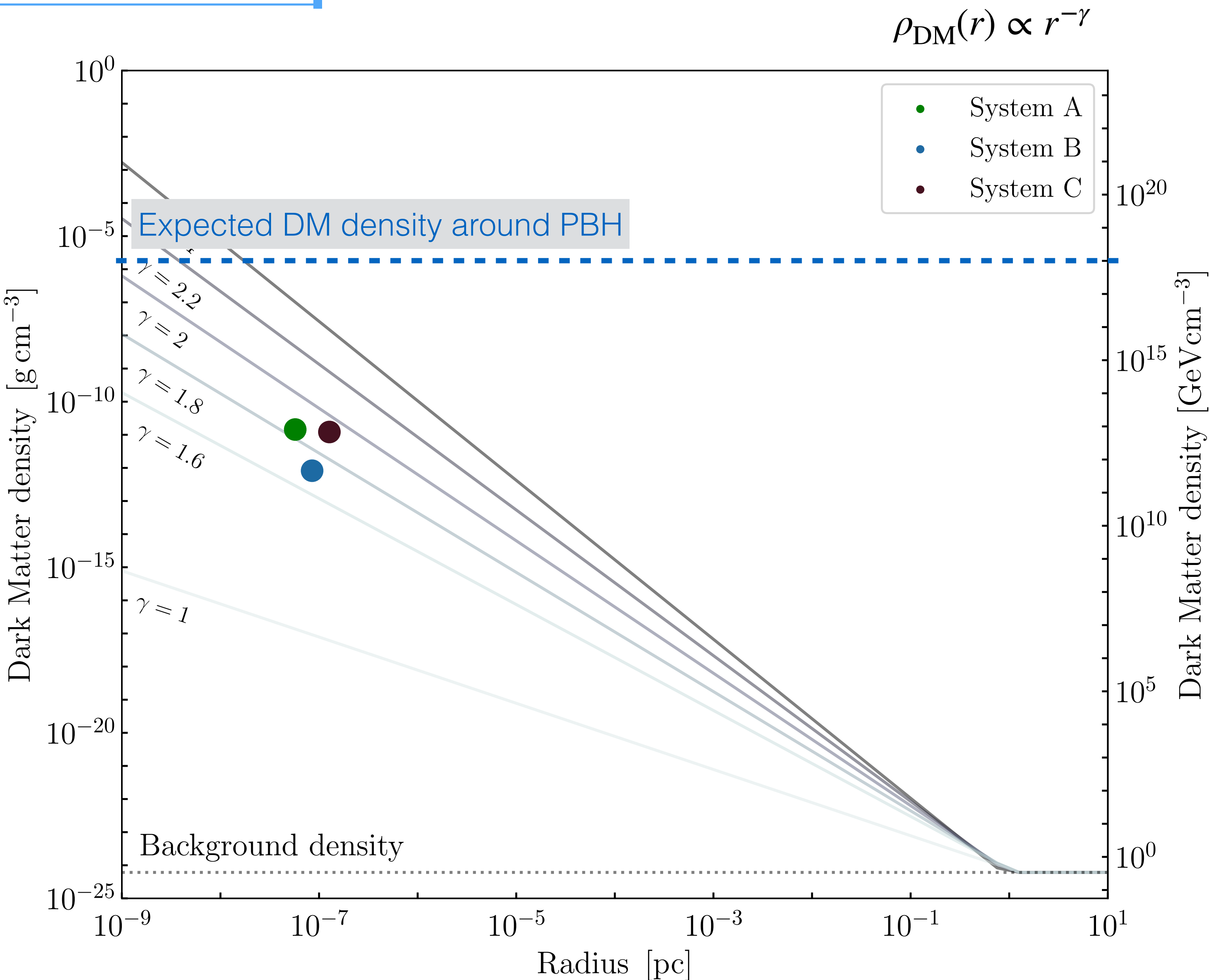
Compare with observed $\dot{P}$ value to infer γ (or equivalently the 'initial' DM density ρ_{DM})

Constraints on the DM spike profile

[Scarcella & **BJK**, [2510.11635](#)]

(Naively?) interpret the anomalous $\dot{P}$ as arising from dynamical friction due to a DM spike:

$$\dot{P} \propto -\frac{M_{\star}}{M_{\text{BH}}} P^2 \rho_{\text{DM}}$$



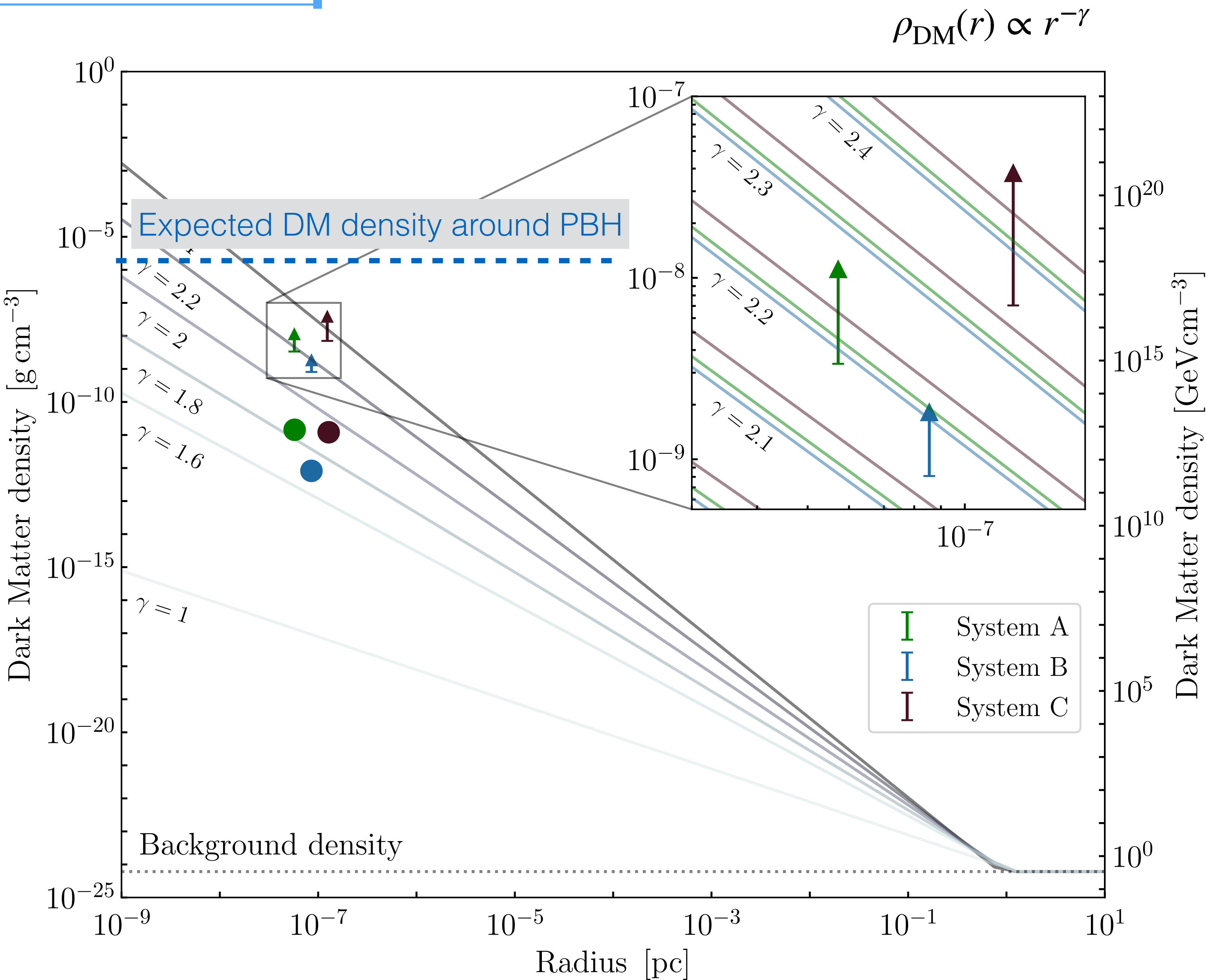
Constraints on the DM spike profile

[Scarcella & **BJK**, [2510.11635](#)]

(Naively?) interpret the anomalous $\dot{P}$ as arising from dynamical friction due to a DM spike:

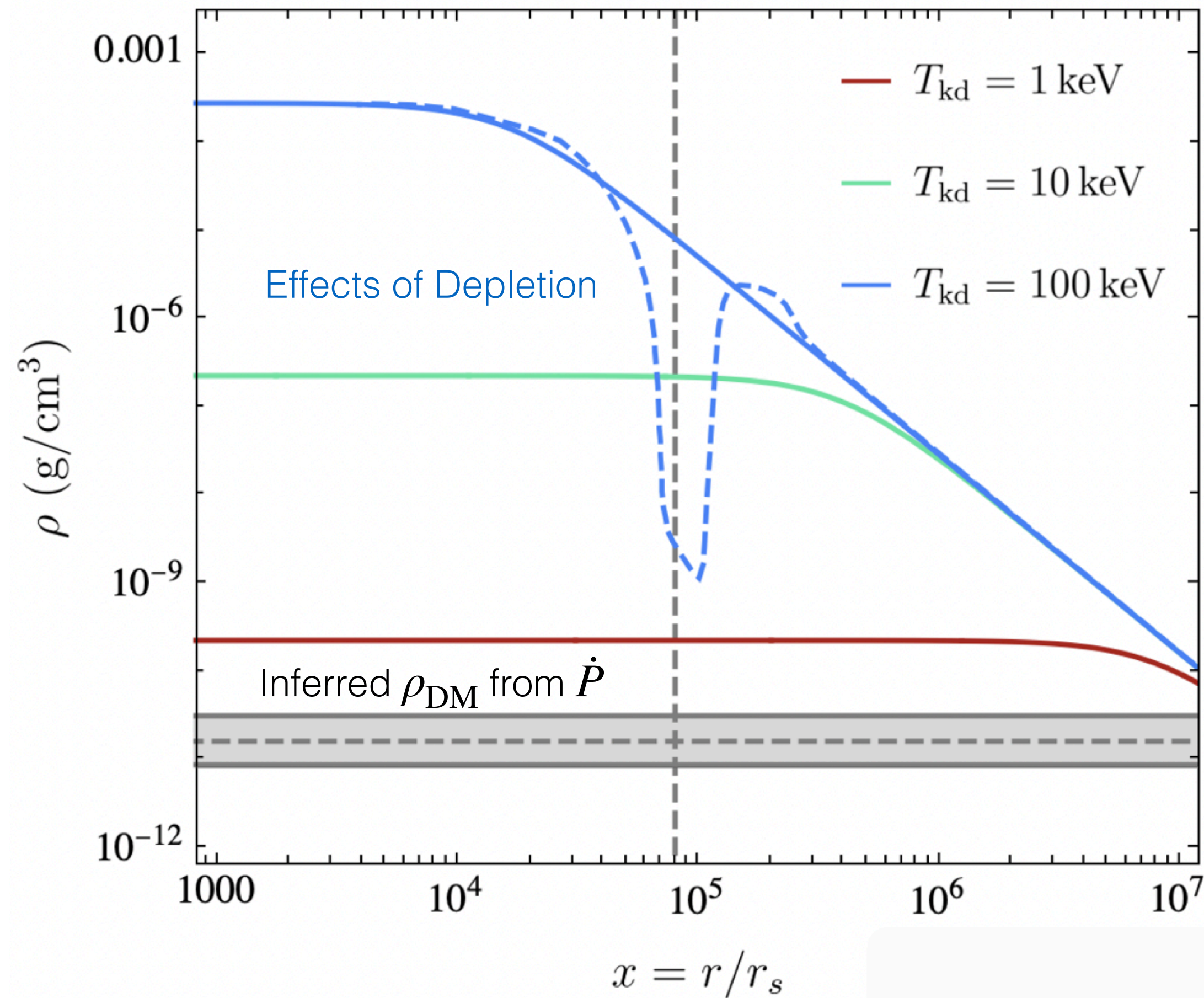
$$\dot{P} \propto -\frac{M_{\star}}{M_{\text{BH}}} P^2 \rho_{\text{DM}}$$

Depletion means that the ‘initial’ DM density must have been many orders of magnitude larger...



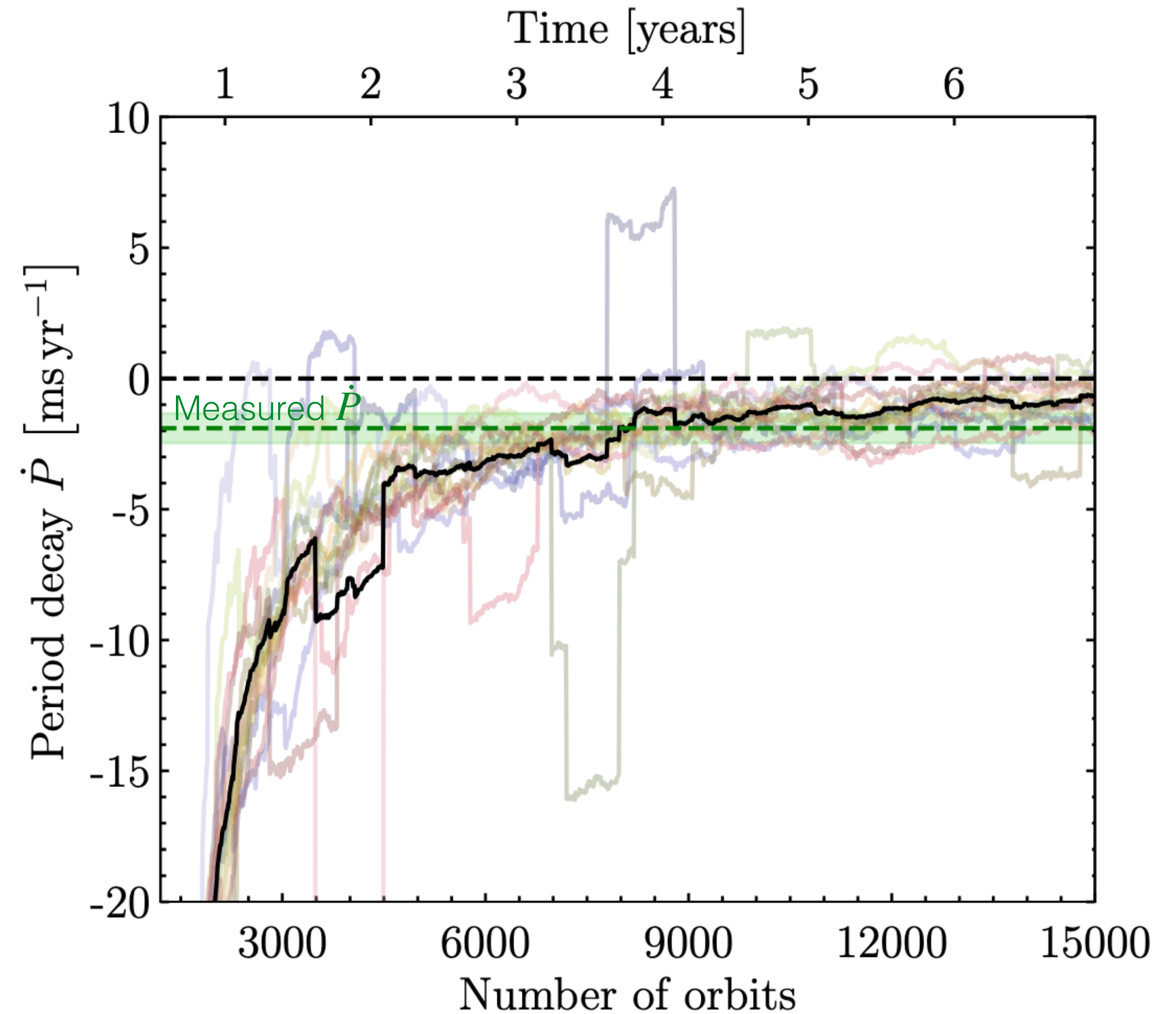
Compatibility with PBHs?

Effects of kinetic decoupling?



[Ireland, [2406.07624](#)]

Depletion over $10^5 - 10^6$ years?



[Scarcella & **BJK**, [2510.11635](#)]

Swallowed Spikes?

In collaboration with
Agnese Tolino, Francesca Scarcella,
V. De Romeri and D. Gaggero

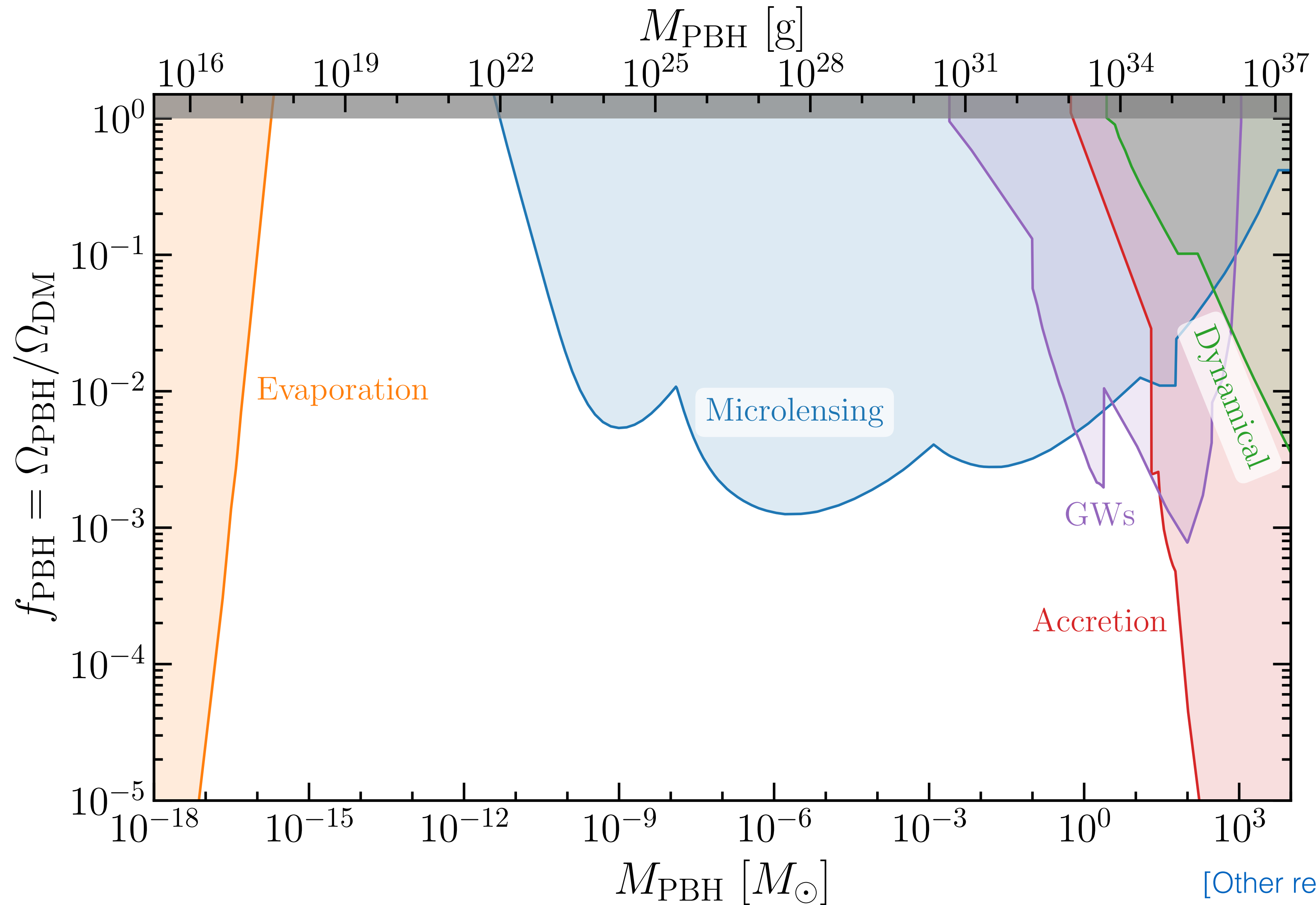
[arXiv:2606.25031](#)



PBH Constraints

[Green & **BJK**, [2007.10722](#)]

[Code online: github.com/bradkav/PBHbounds]

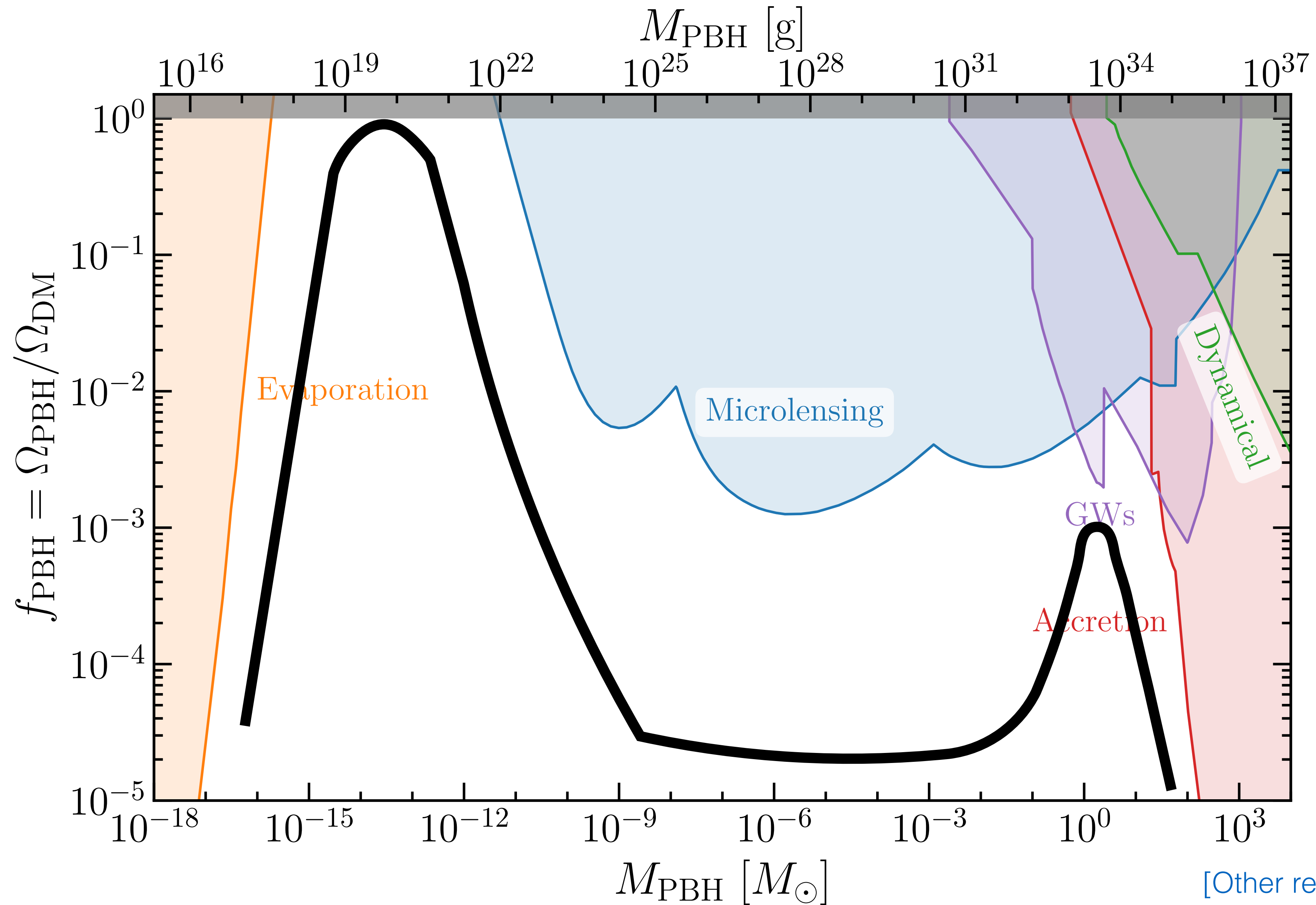


[Other reviews: [1801.05235](#),
[2002.12778](#), [2006.02838](#)]

PBH Constraints

[Green & **BJK**, 2007.10722]

[Code online: github.com/bradkav/PBHbounds]



[Other reviews: [1801.05235](#),
[2002.12778](#), [2006.02838](#)]

Instead of particle DM, we consider a population of light PBHs (**IPBHs**), with masses $m \in [10^{-16}, 10^{-5}] M_{\odot}$, around a central heavy (**hPBH**) PBH, $M \in [1, 10^3] M_{\odot}$ (QCD + SMBH seeds)

PBHs are not expected to be born with significant peculiar velocities, so the light PBHs may be captured!

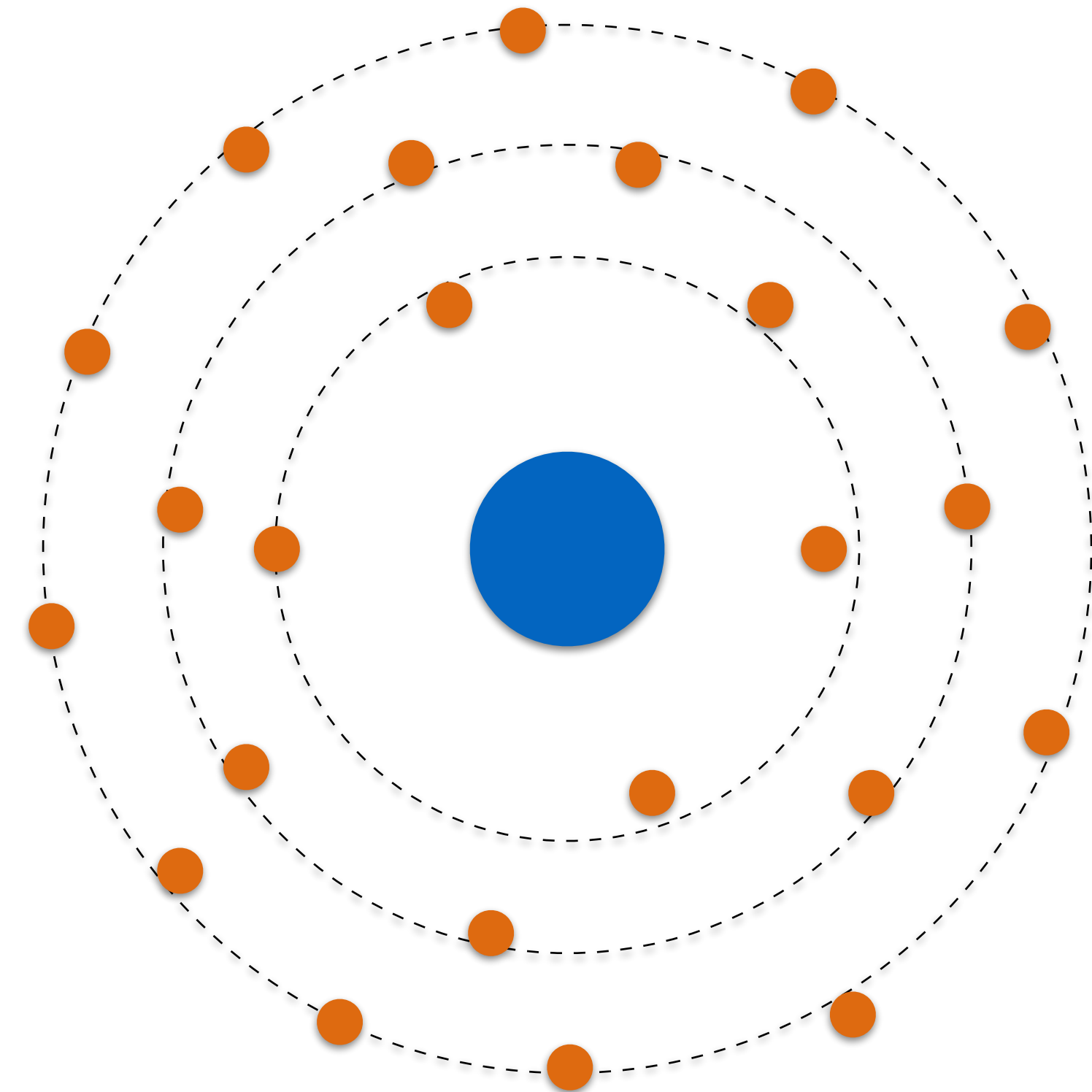
Can a spike made of PBHs form at all?

This would require sufficient torques τ on the IPBH-hPBH system.

The accumulated angular momentum

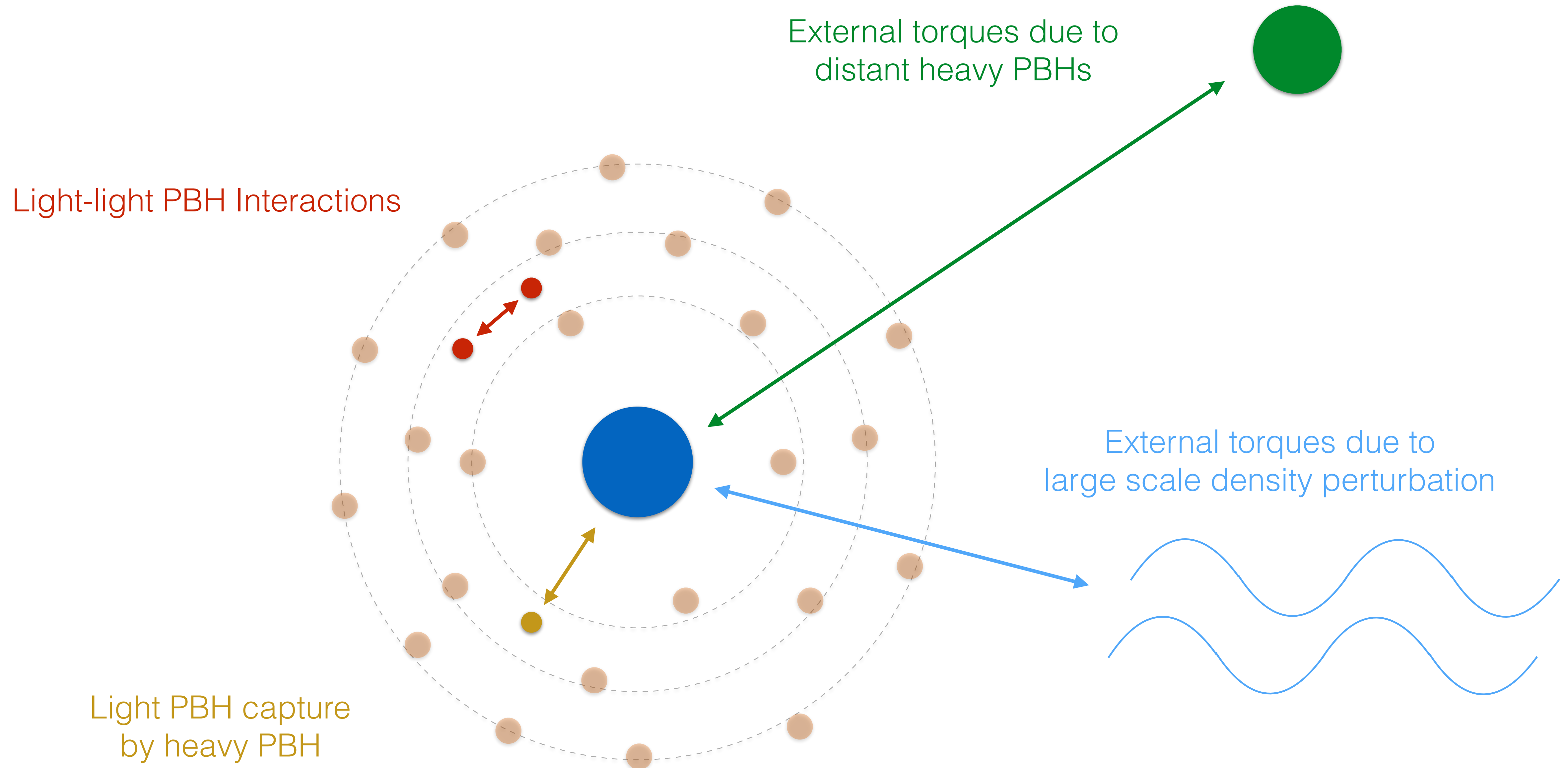
$$\ell(r_{\text{ta}}) = \int_0^{t_{\text{ff}}} \frac{\tau(t)}{m} dt$$

must exceed the threshold for capture, $\ell_{\text{min}} = 4GM/c$.



Sources of Torque

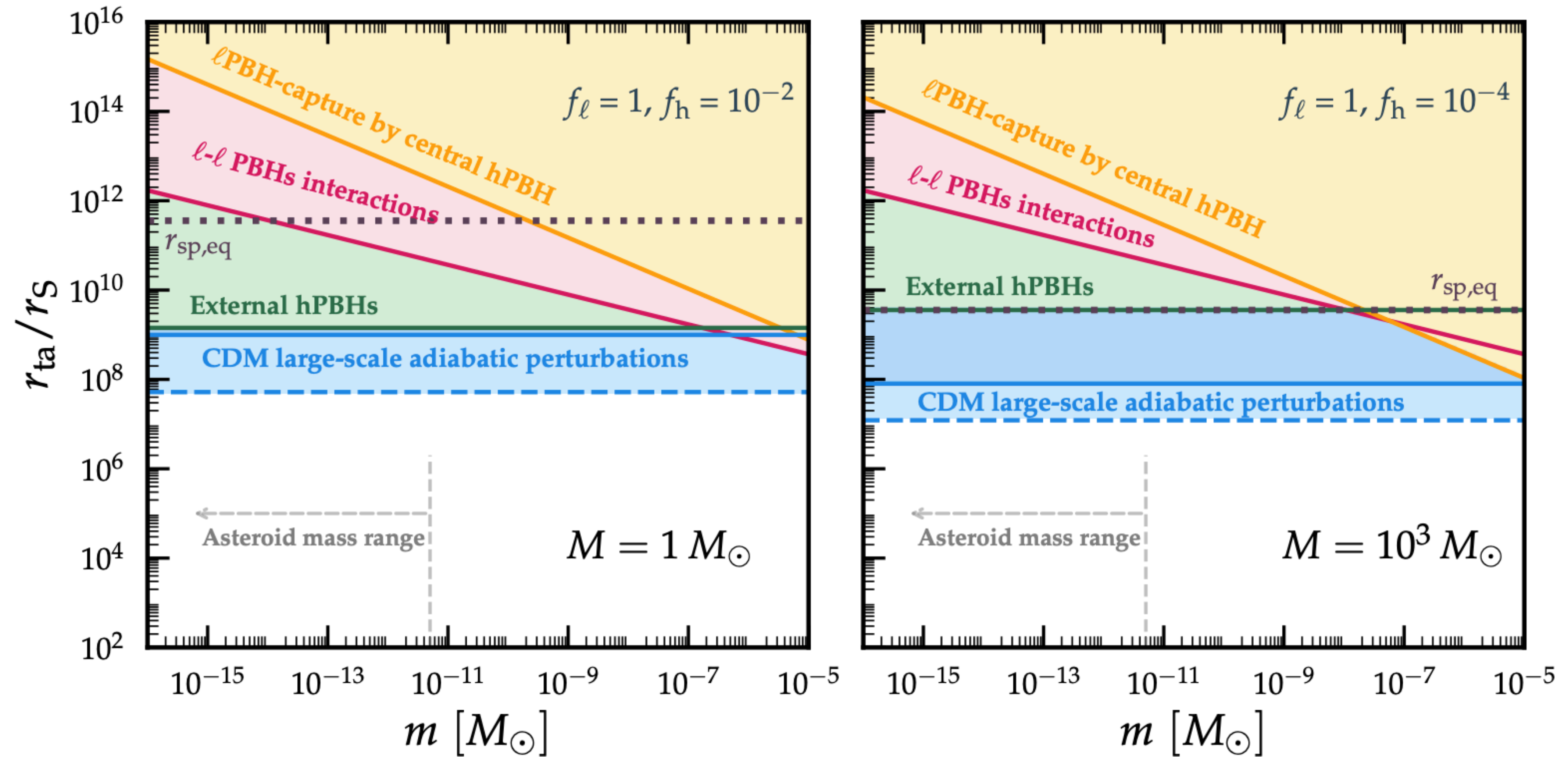
[Tolino, Scarcella, **BJK**, De Romeri & Gaggero, [2606.25031](#)]



Swallowed PBH Spikes

[Tolino, Scarcella, **BJK**, De Romeri & Gaggero, [2606.25031](#)]

Assuming that the light PBHs make up ~all of the DM:

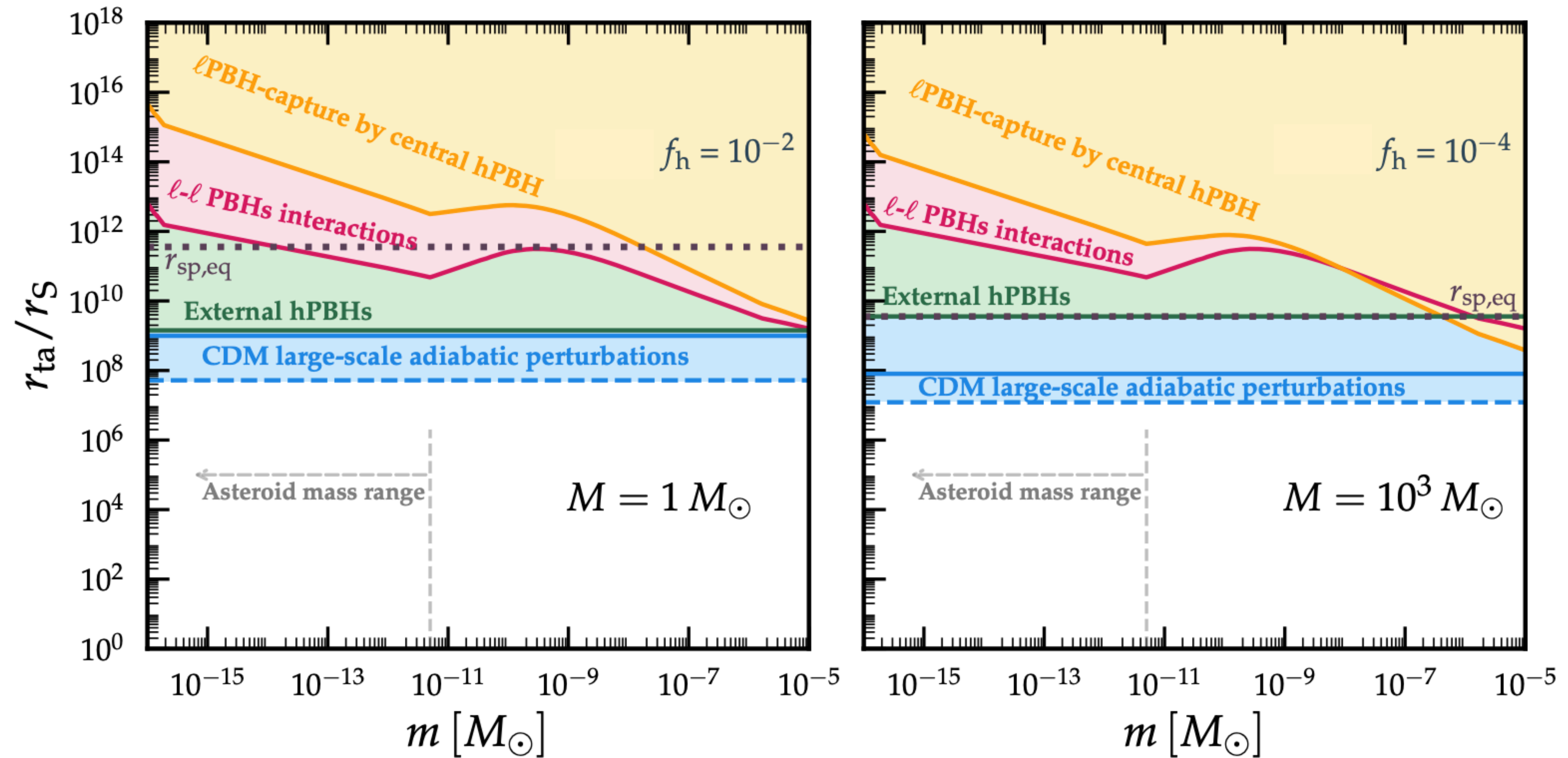


White regions are *swallowed* by the central PBH of mass M

Swallowed PBH Spikes

[Tolino, Scarcella, **BJK**, De Romeri & Gaggero, [2606.25031](#)]

Saturating the light PBH abundance based on current (microlensing/evaporation) constraints:

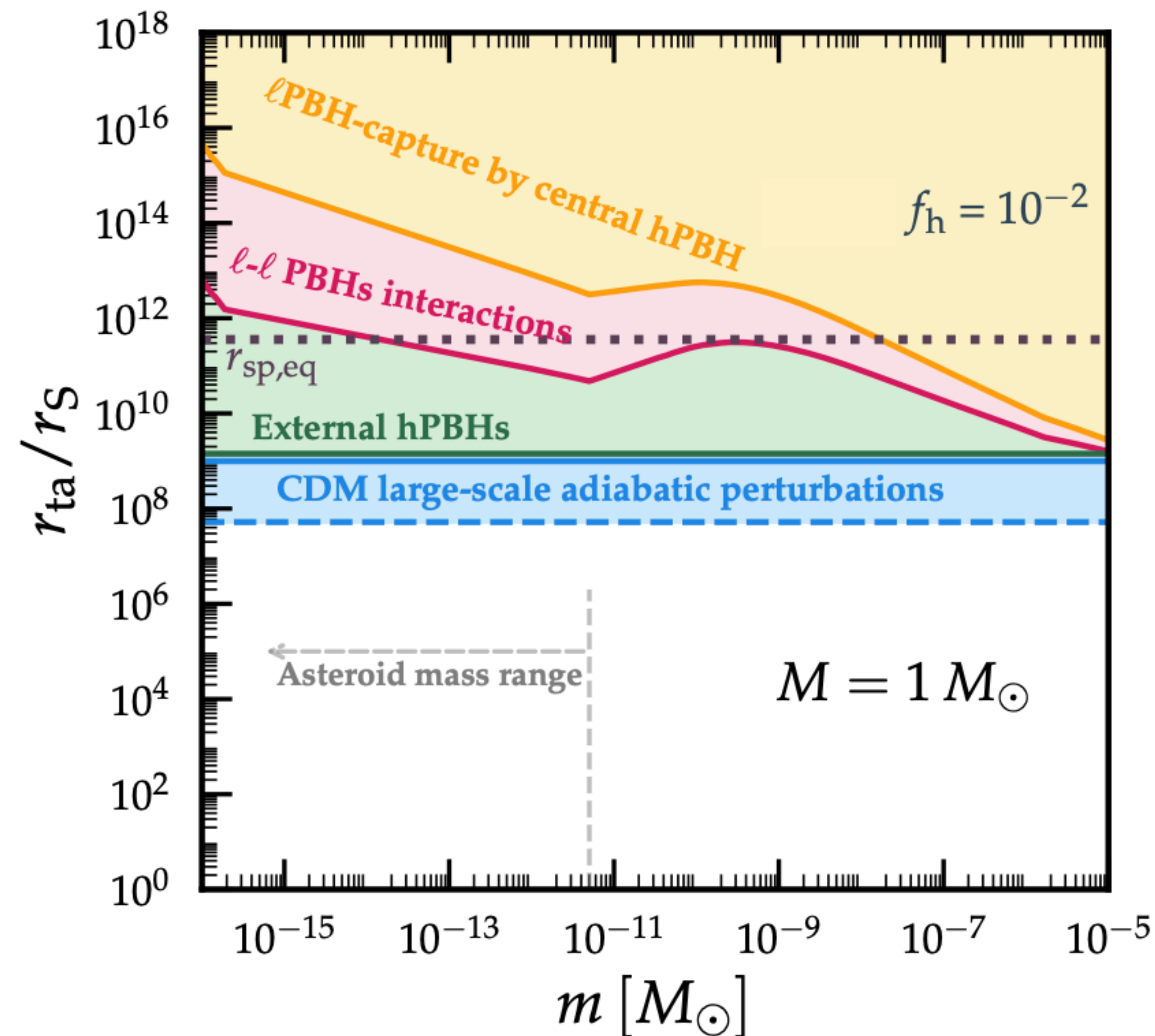


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[Tolino, Scarcella, **BJK**, De Romeri & Gaggero, [2606.25031](#)]

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<1 % of the spike mass is swallowed

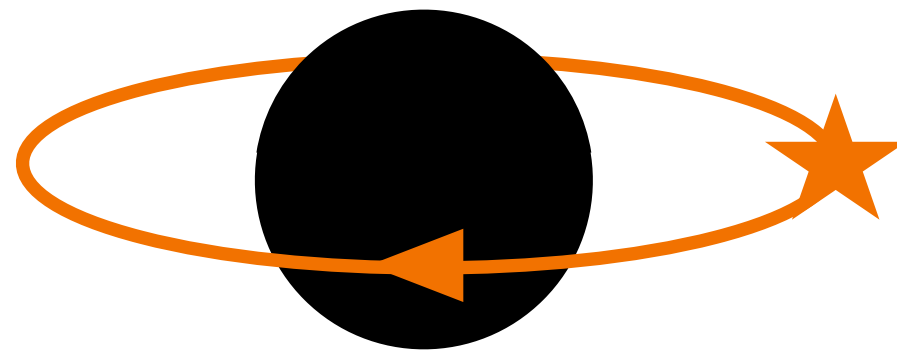
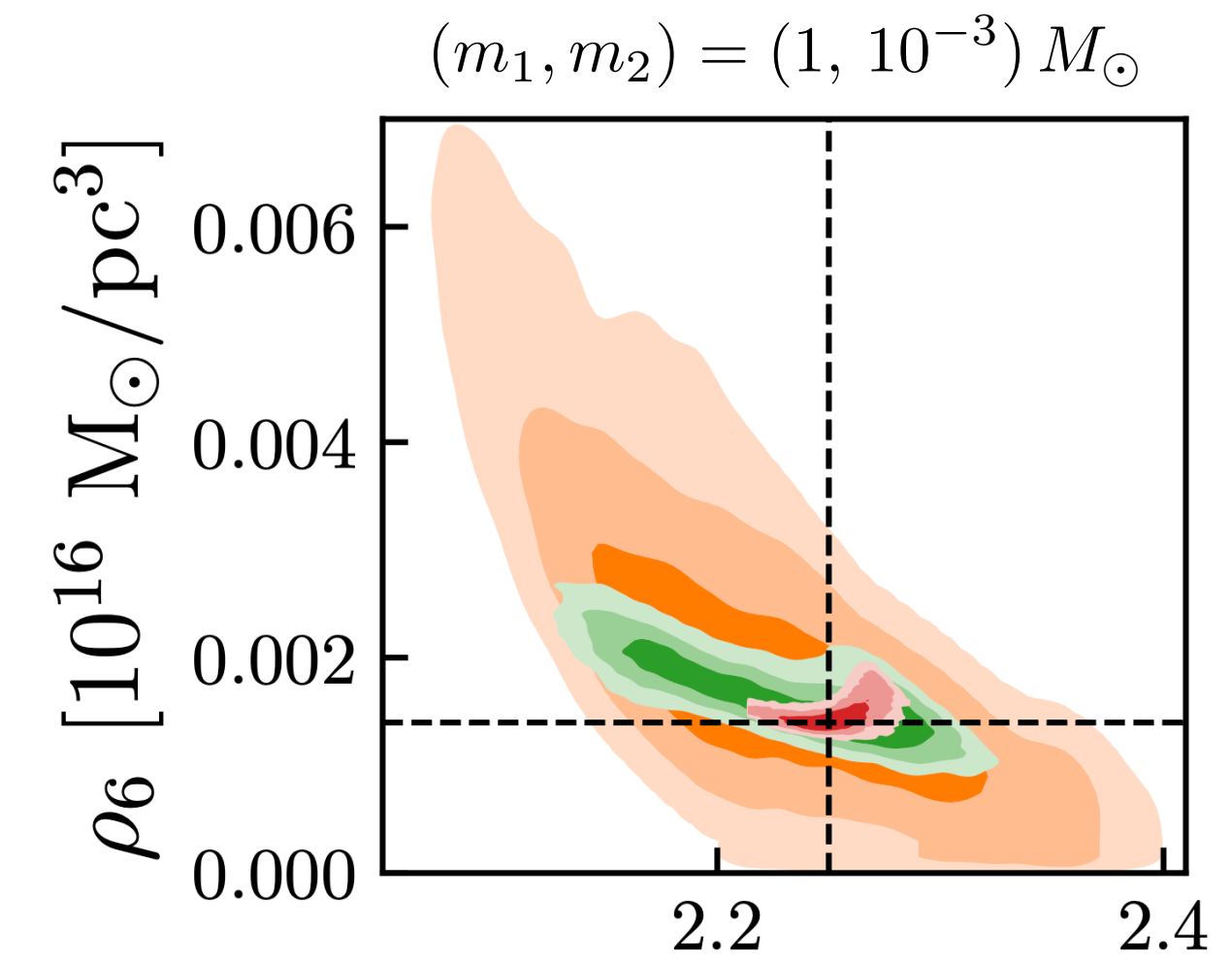
But this is the central region ($r < 10^8 r_s$), where some of the most interesting signals arise!

Still need to understand the subsequent dynamics and determine the 'final' spike density profile...

White regions are *swallowed* by the central PBH of mass M

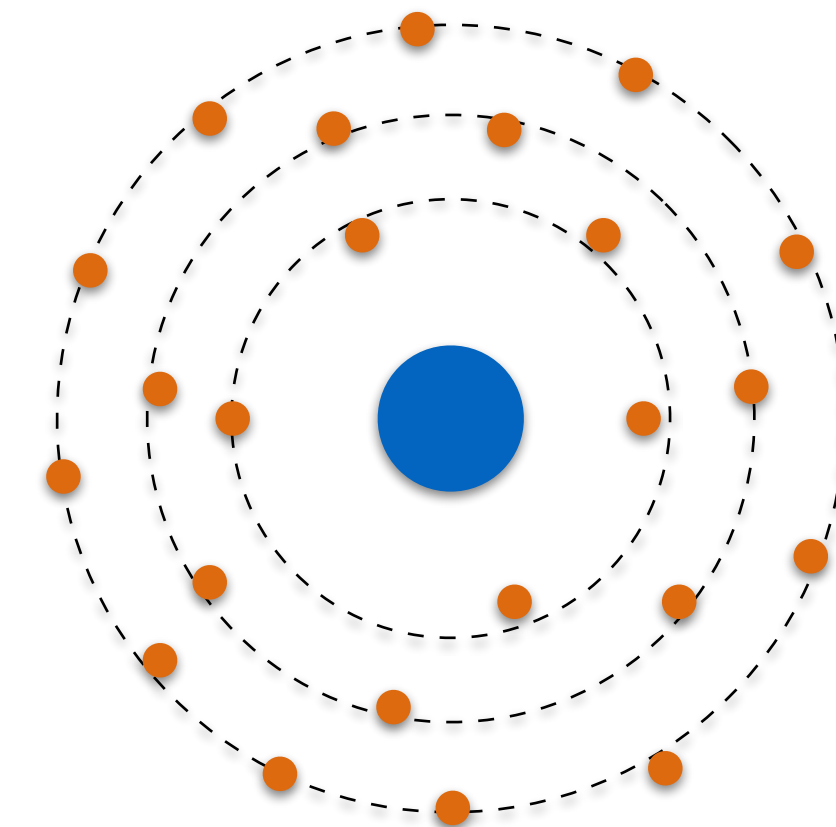
Conclusions

If near-future GW observatories detect PBH mergers, they should also be able to detect and characterize the DM spikes around them



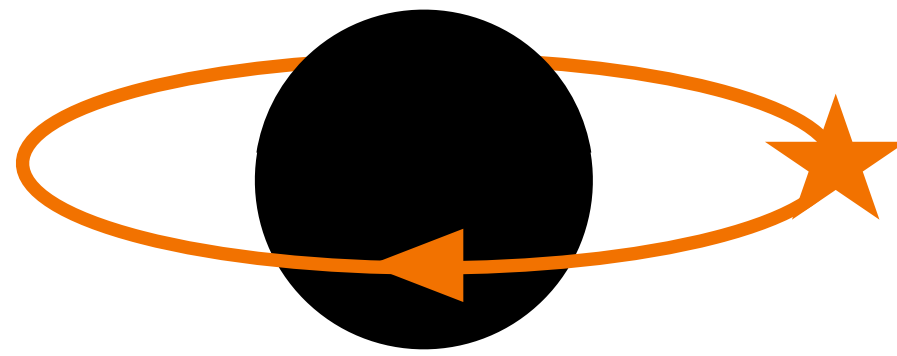
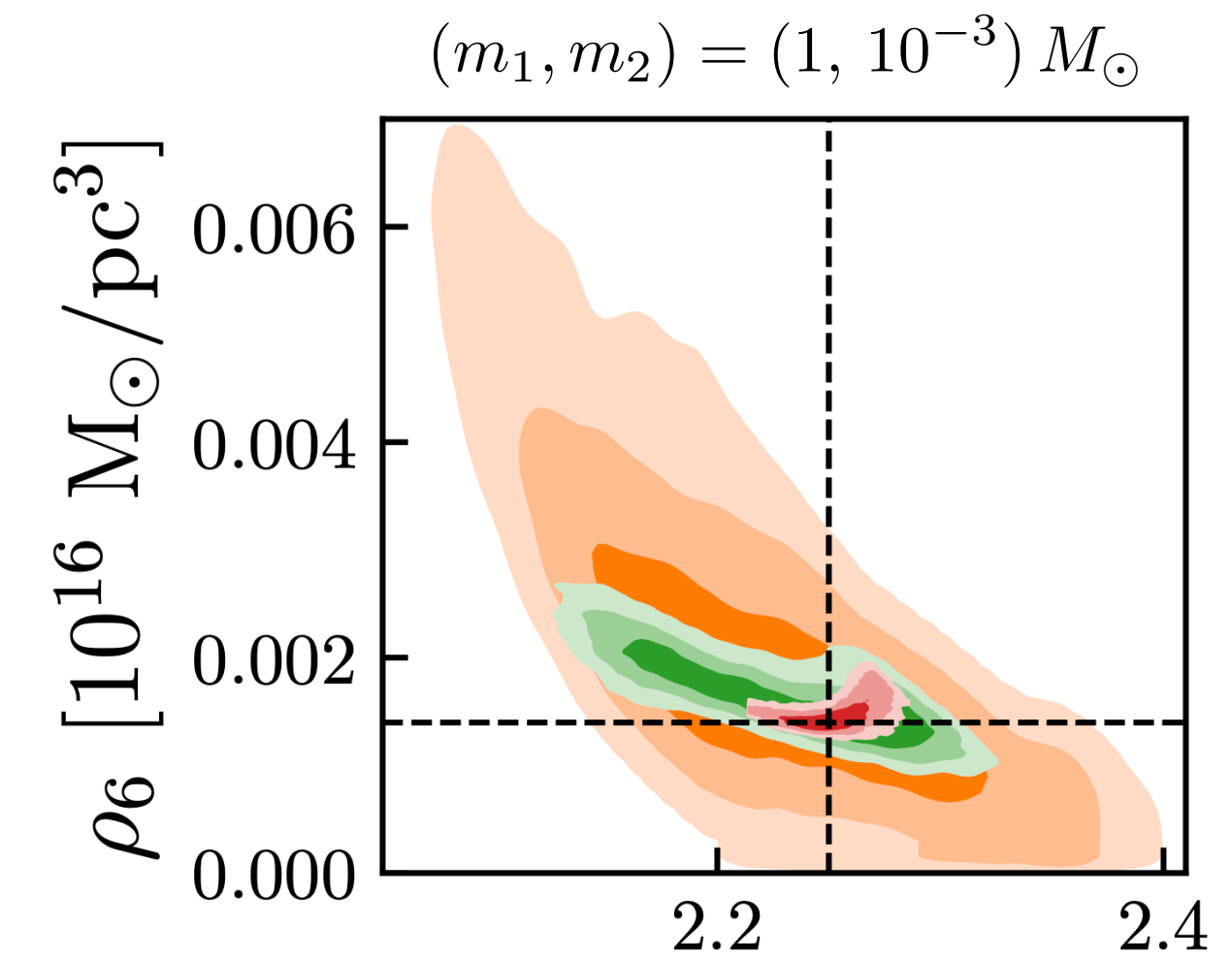
Similar processes could also lead to signatures in LMXBs, but modeling and interpreting these things is not trivial

This is not limited to particle-like DM, and we're making progress in understanding PBH spikes around PBHs (and their signatures)



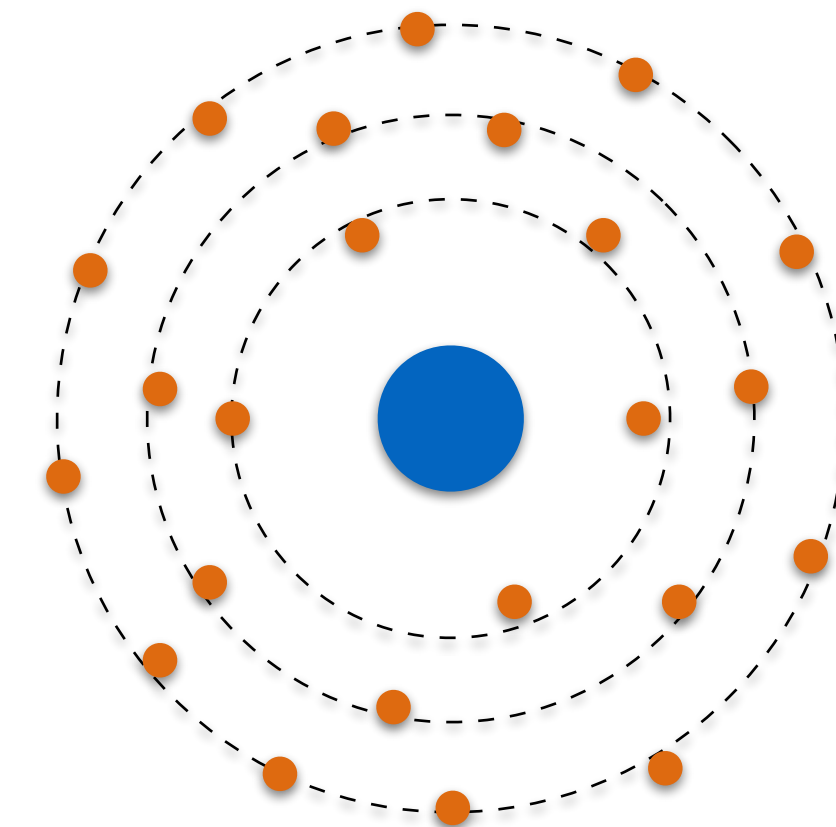
Conclusions

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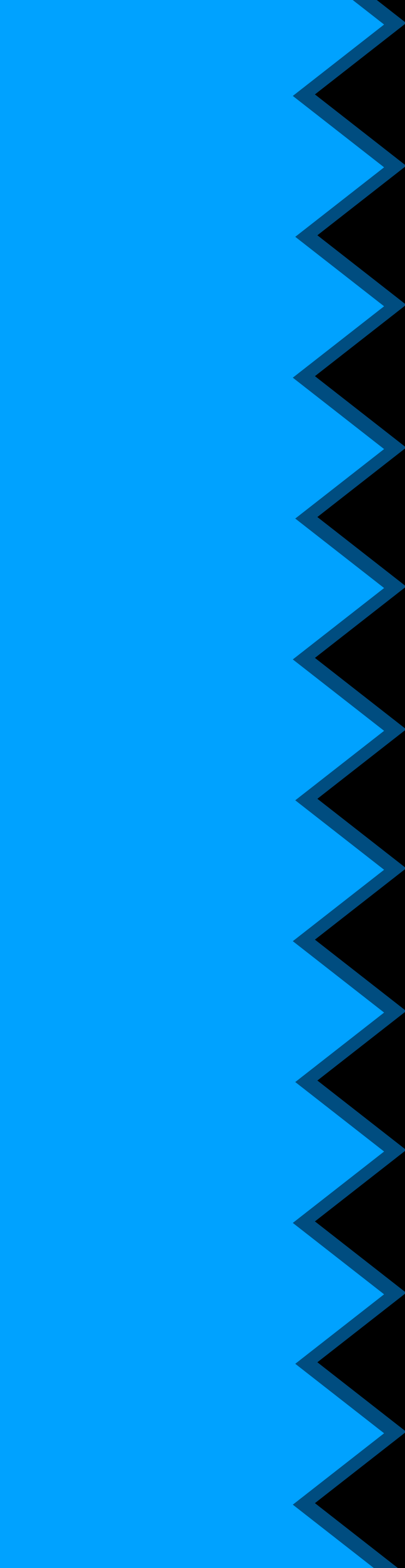


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Thank you!



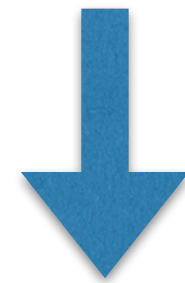
Backup Slides

Adiabatic Growth

- BH grows by gas accretion from an infinitesimal seed, at the centre of an NFW DM halo
- DM density can be enhanced within the ‘spike radius’ r_{sp} , comparable to the sphere of influence of the BH

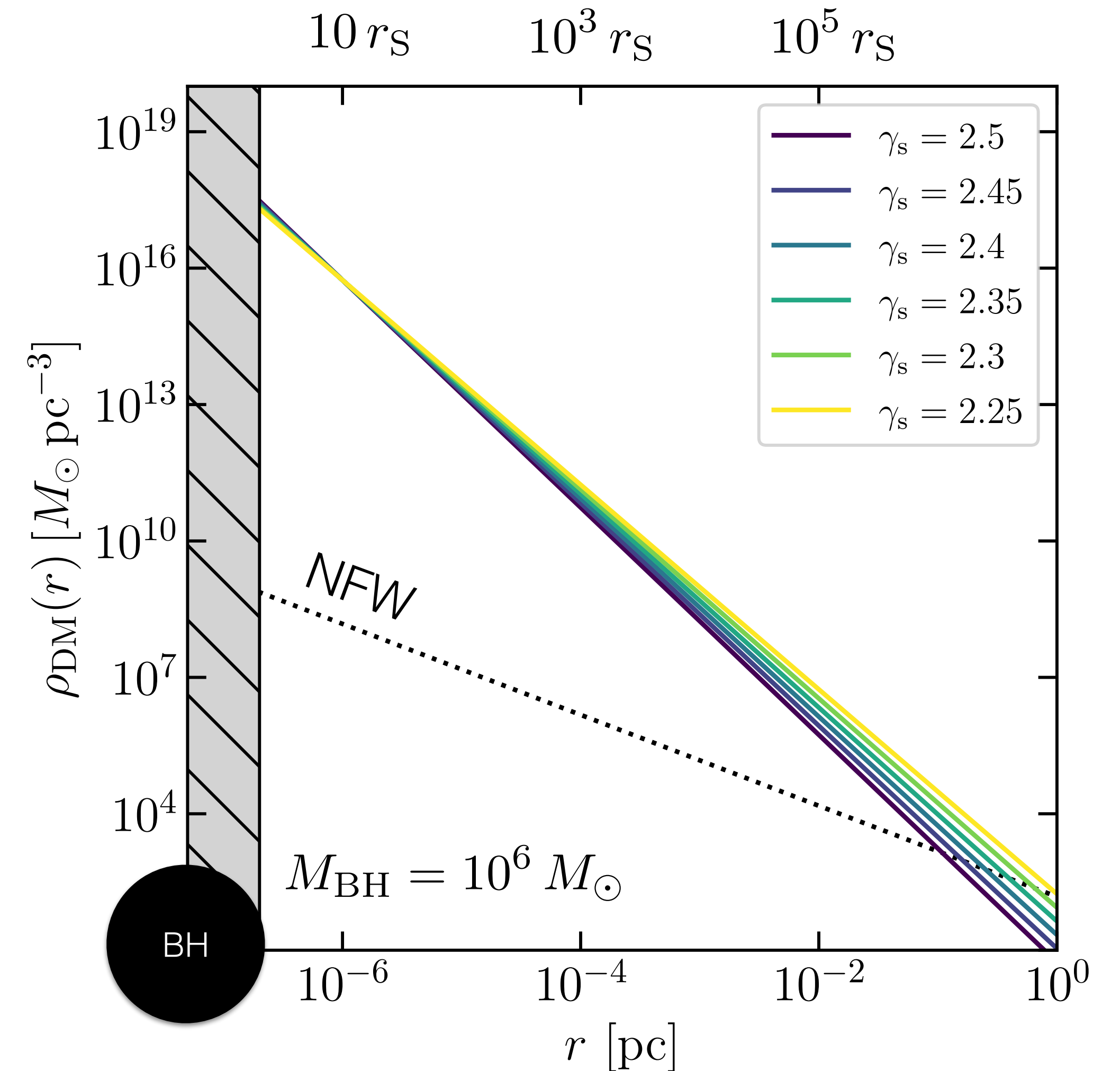
$$\int_0^{r_{\text{sp}}} 4\pi r^2 \rho_{\text{NFW}}(r) dr = \beta M_{\text{BH}} \quad [\beta \approx 0.1]$$

- Adiabatic:** Timescale for growth is much longer than the dynamical timescale of the DM



Angular momentum $\mathbf{L}$ and radial action I are preserved, allowing us to map between initial and final DM energy $\mathcal{E}$.

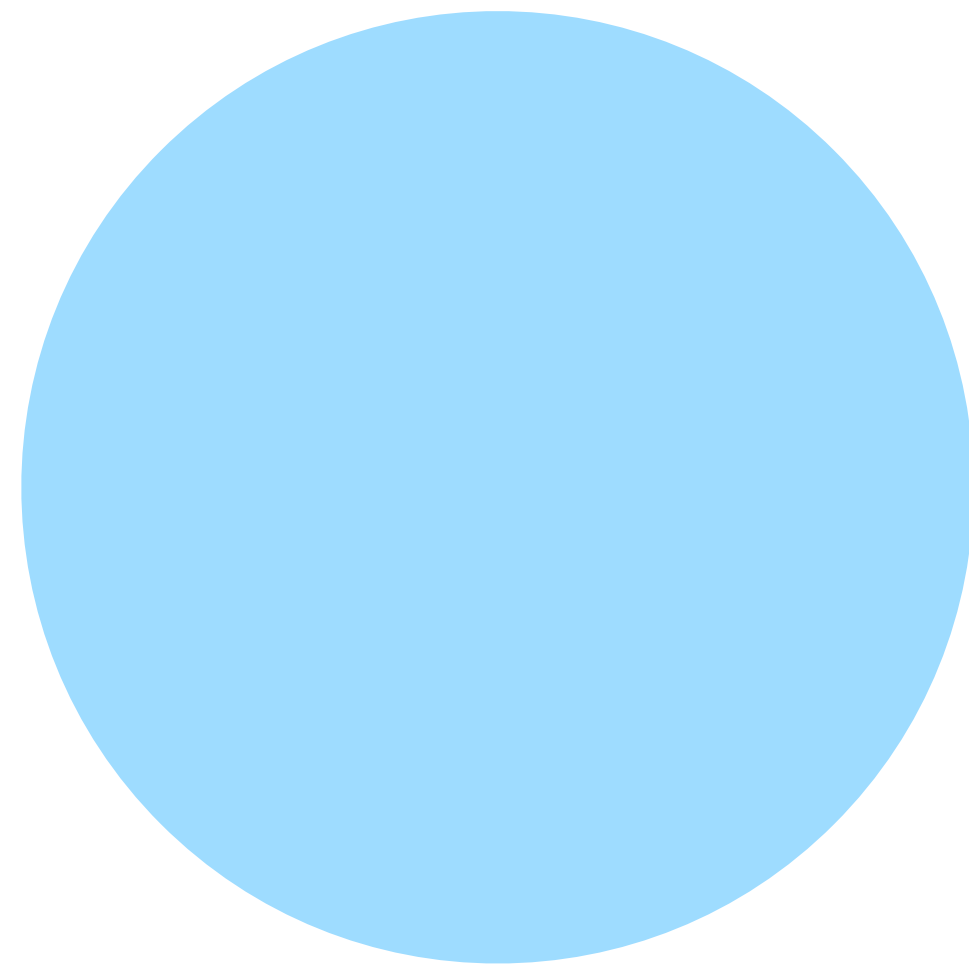
$$\text{Radial Action: } I(\mathcal{E}, L) = \frac{1}{\pi} \int_{r_{\text{min}}}^{r_{\text{max}}} v_r(r, \mathcal{E}, L) dr$$



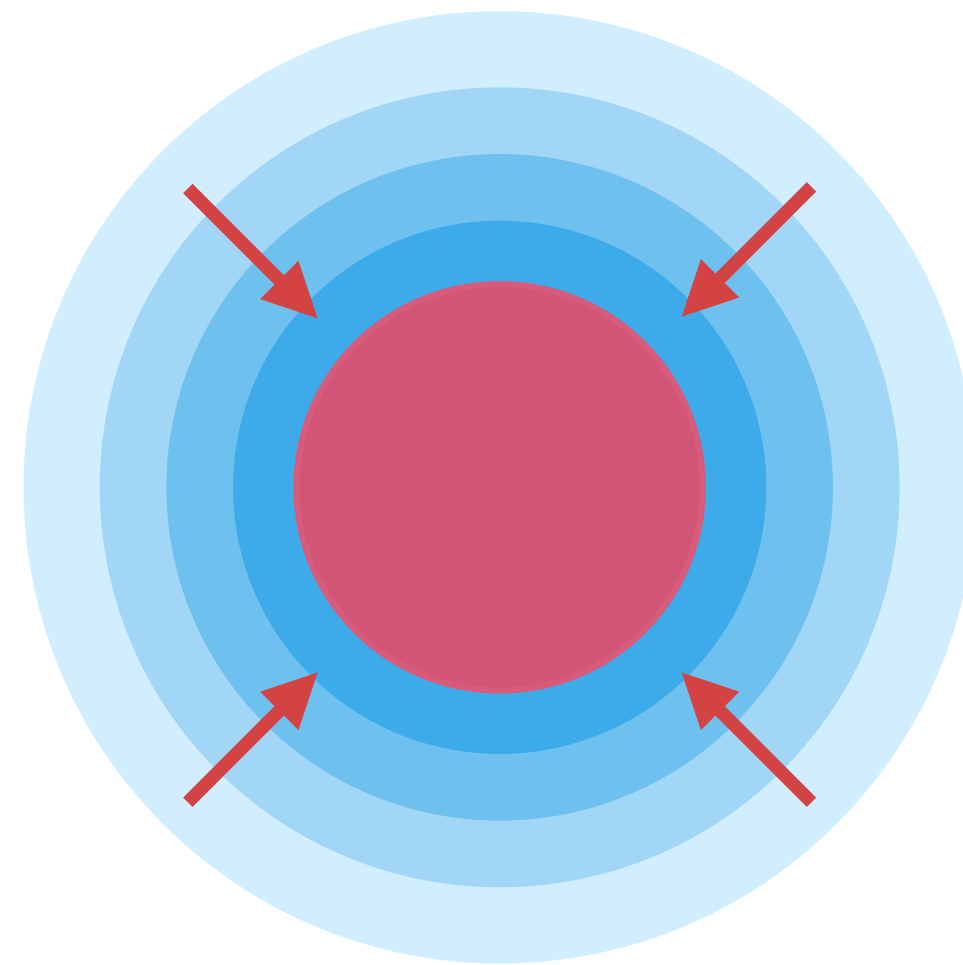
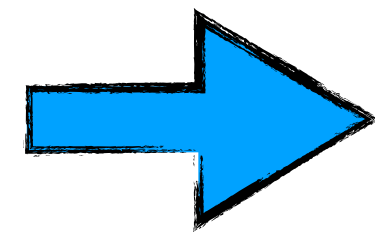
DM orbits contract, leading to steep ‘spike’ density profile: $\rho_{\text{DM}} = \rho_{\text{sp}} \left(\frac{r_{\text{sp}}}{r} \right)^{\gamma_{\text{sp}}}$

Dark Matter Mounds

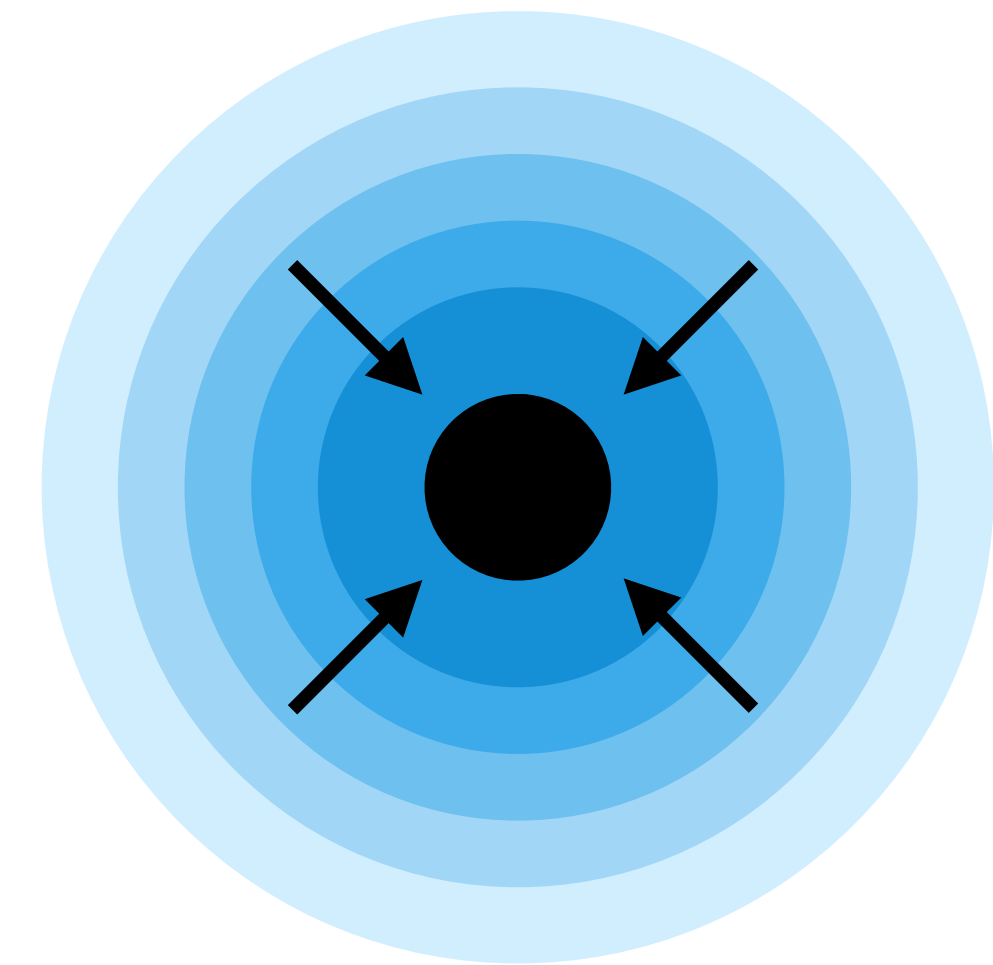
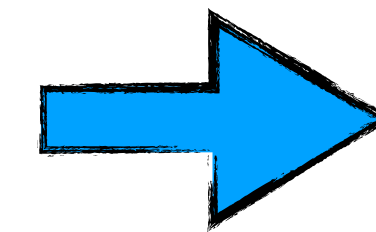
*Precise details of formation affect slope and density of DM very close to BH



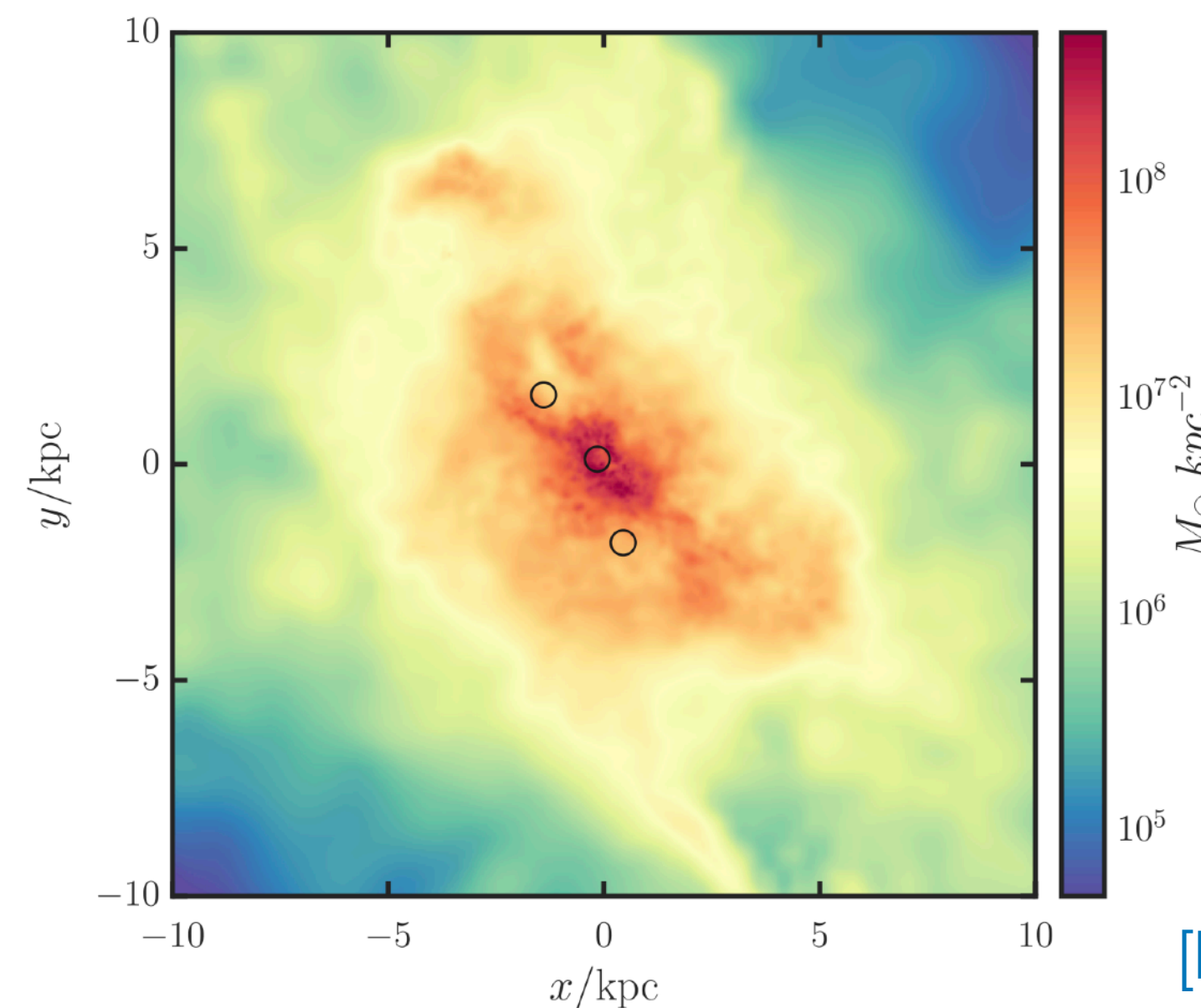
NFW Dark Matter Halo
at high redshift $z \gtrsim 15$



Supermassive 'star'



Direct Collapse Black Hole
+ Dense **DM Spike/Mound**



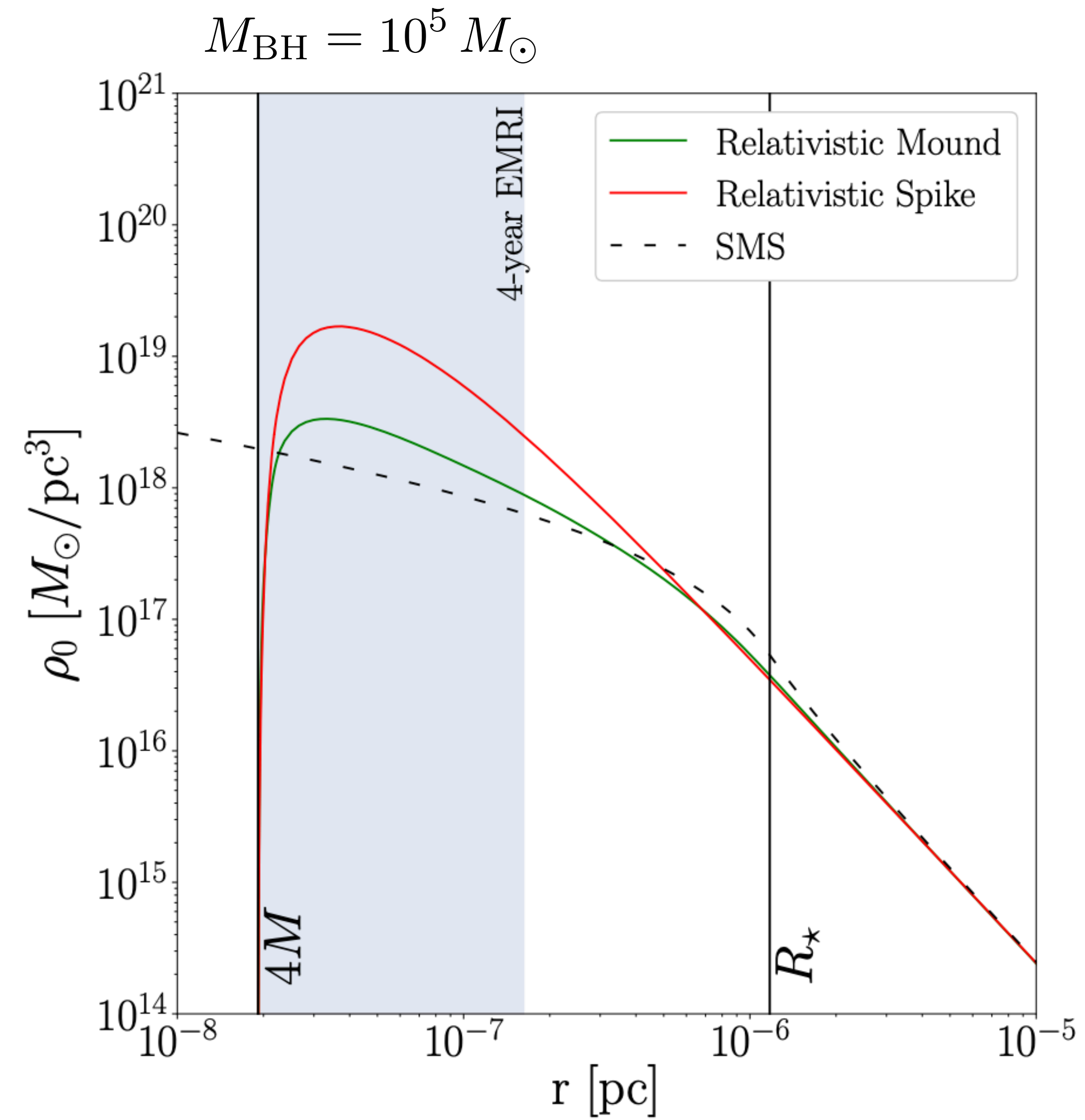
$$m_{\text{DCBH}} \sim 10^3 - 10^5 M_{\odot}$$

The BH may experience subsequent growth to become supermassive

[Bertone et al. (including **BJK**), [2404.08731](#)]
[Caiozzo et al. (including **BJK**), [2512.09985](#)]

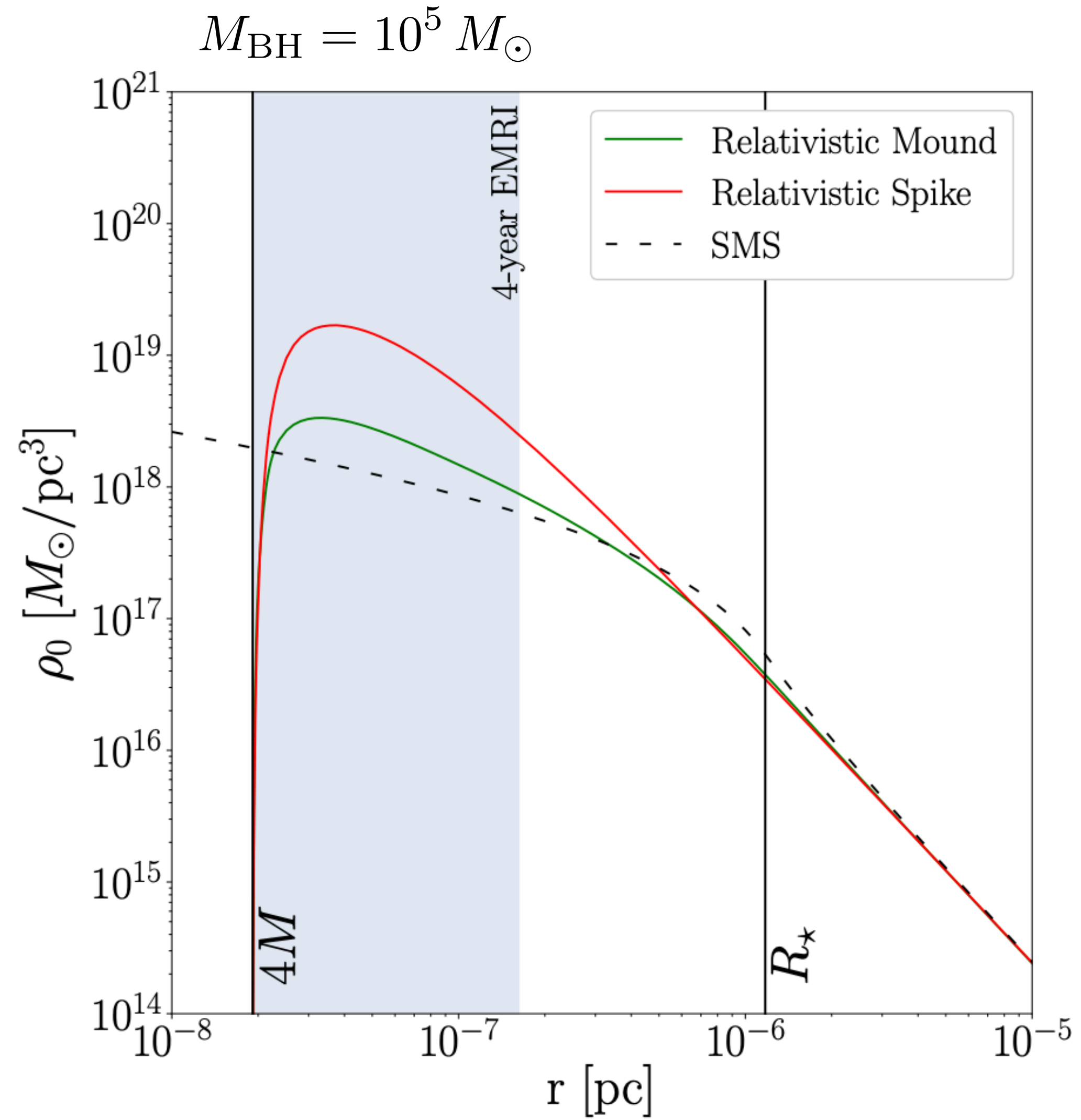
[Dunn et al., [1803.01007](#)]

Dark Matter Mounds

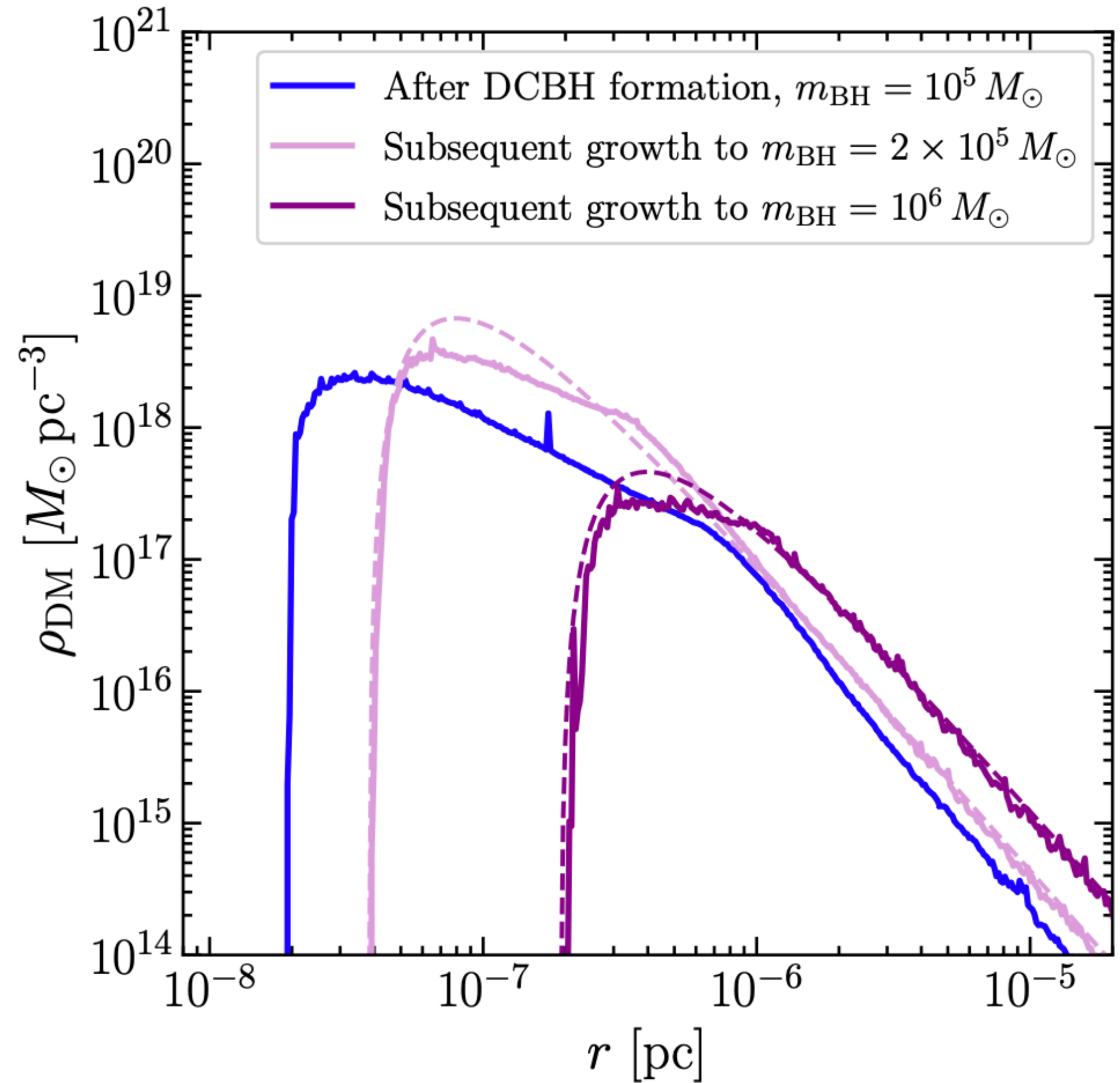


[Caiozzo et al. (including **BJK**), [2512.09985](#)]

Dark Matter Mounds



[Caiozzo et al. (including **BJK**), [2512.09985](#)]



[Bertone et al. (including **BJK**), [2404.08731](#)]

Feedback

Follow semi-analytically the phase space distribution of DM:

$$f = \frac{dN}{d^3\mathbf{r} d^3\mathbf{v}} \equiv f(\mathcal{E})$$

$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Each particle receives a ‘kick’ through gravitational scattering

$$\mathcal{E} \rightarrow \mathcal{E} + \Delta\mathcal{E}$$

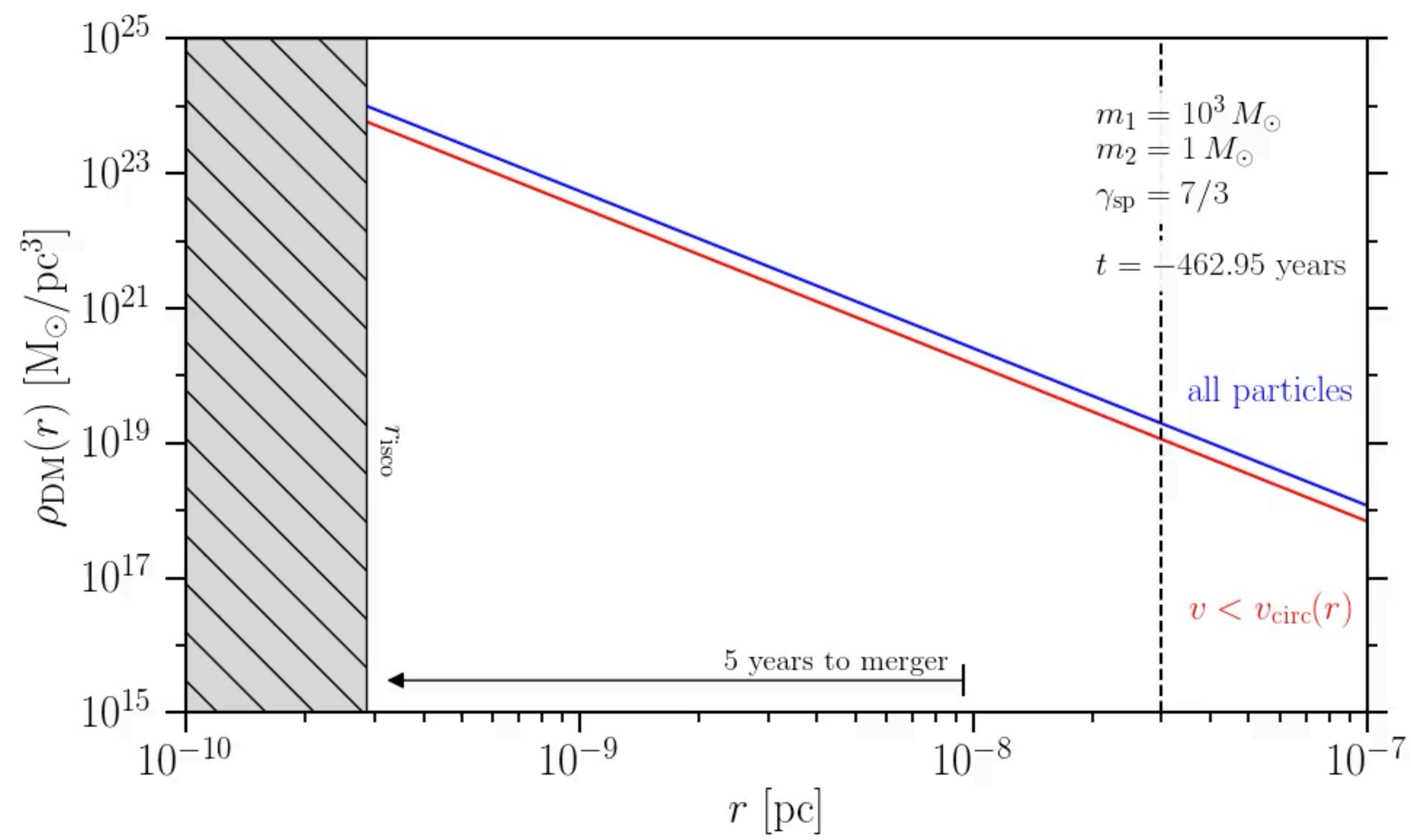
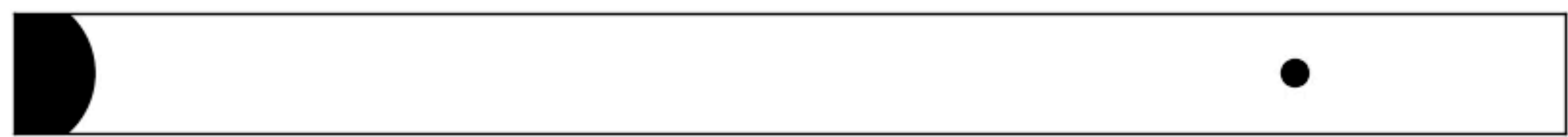
Reconstruct density from distribution function:

$$\rho(r) = \int d^3\mathbf{v} f(\mathcal{E})$$



Compact object scatters with all DM particles within ‘torus’ of influence over one orbit

Feedback

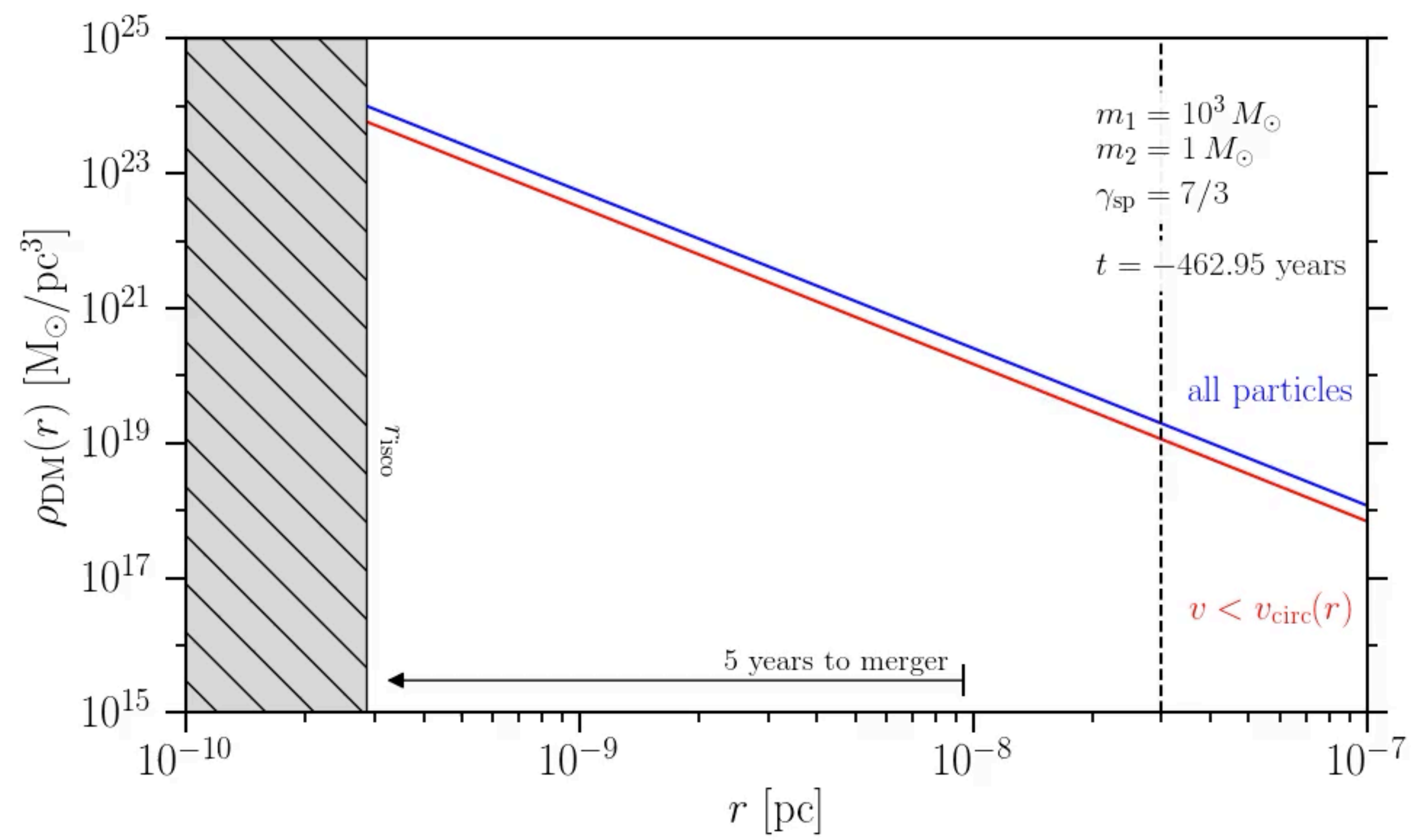
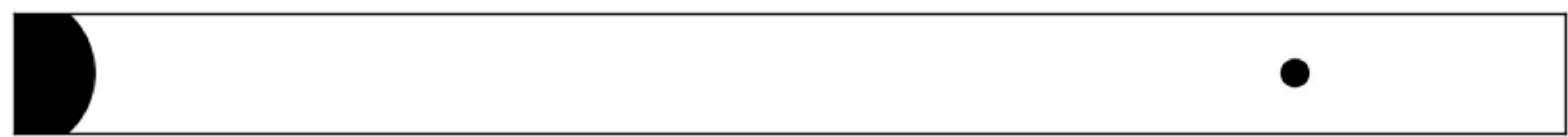


Find that the density of the DM spike is depleted (and replenished...)

Size of the dephasing effect is **reduced from $\mathcal{O}(1)$ to $\mathcal{O}(1\%)$.**

“Strength” of feedback scales roughly as $q^2 = (m_2/m_1)^2$

Feedback



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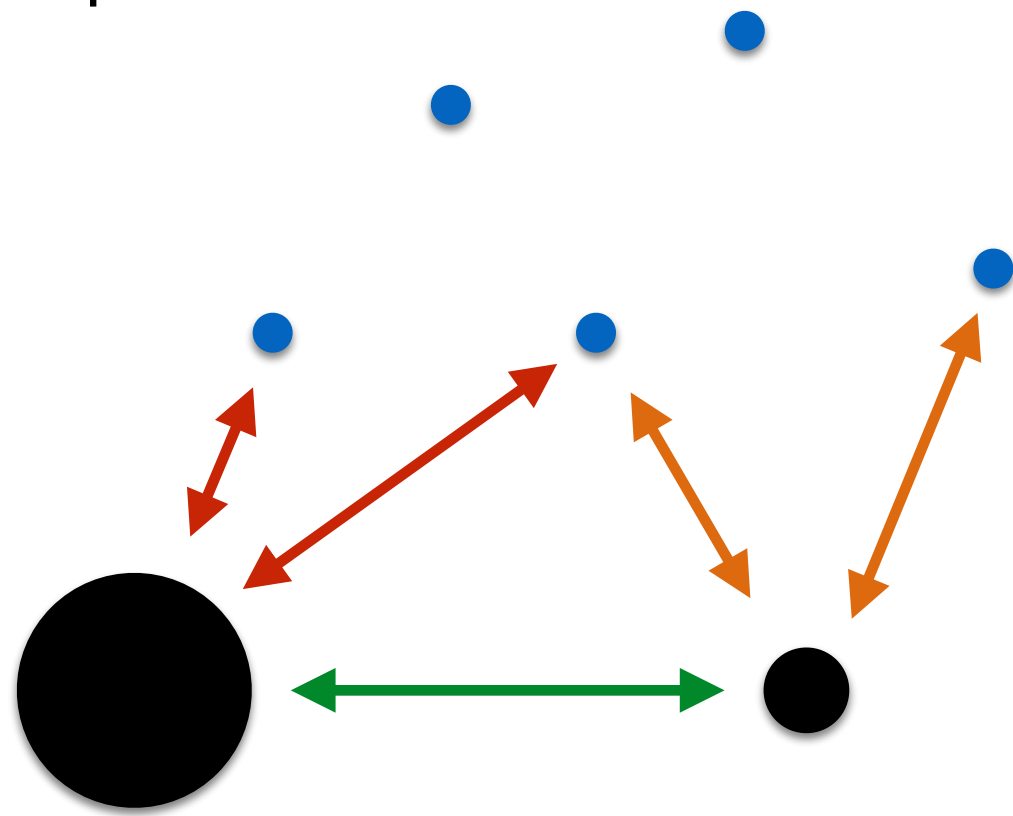
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N-body Simulations

Eventually need to expand and verify our description of dynamical friction and feedback in the DM spike

NbodyIMRI: Newtonian N-body solver tailored to DM spikes.

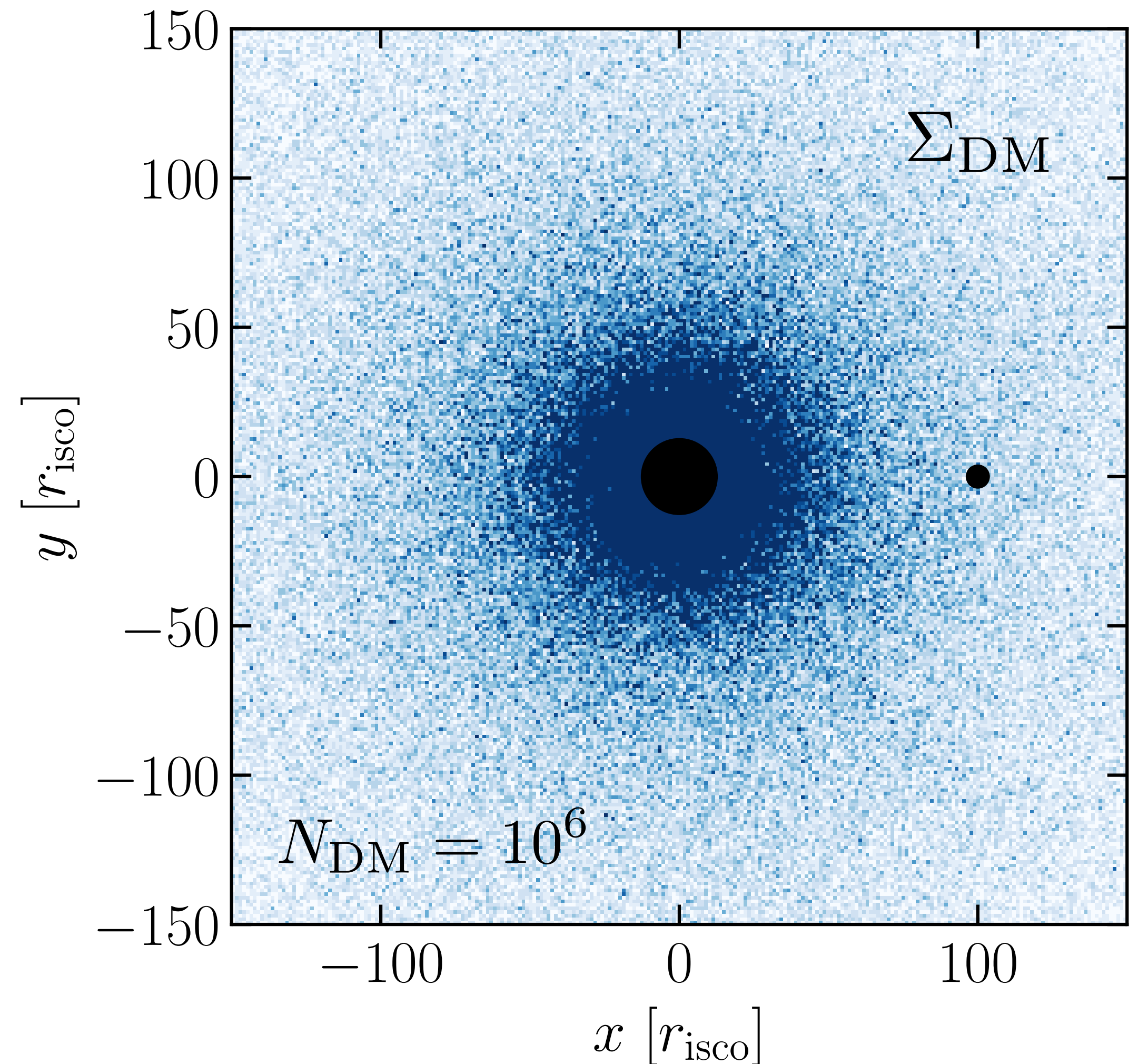


Neglect GW emission and *ignore DM-DM interparticle forces*.

Focus on understanding co-evolution of spike and binary.

[**BJK** et al., [2402.13762](#)]

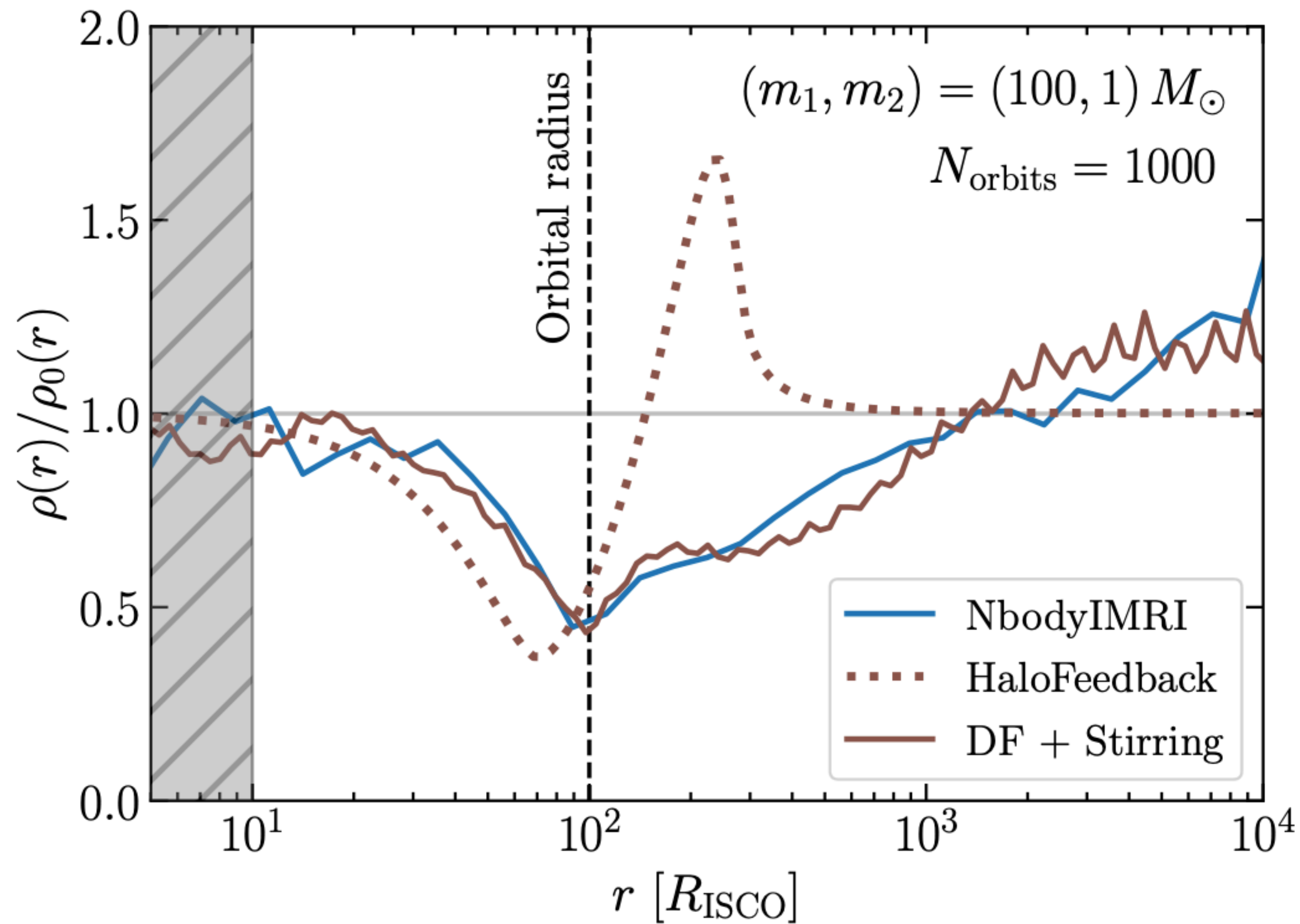
[Code here: github.com/bradkav/NbodyIMRI]



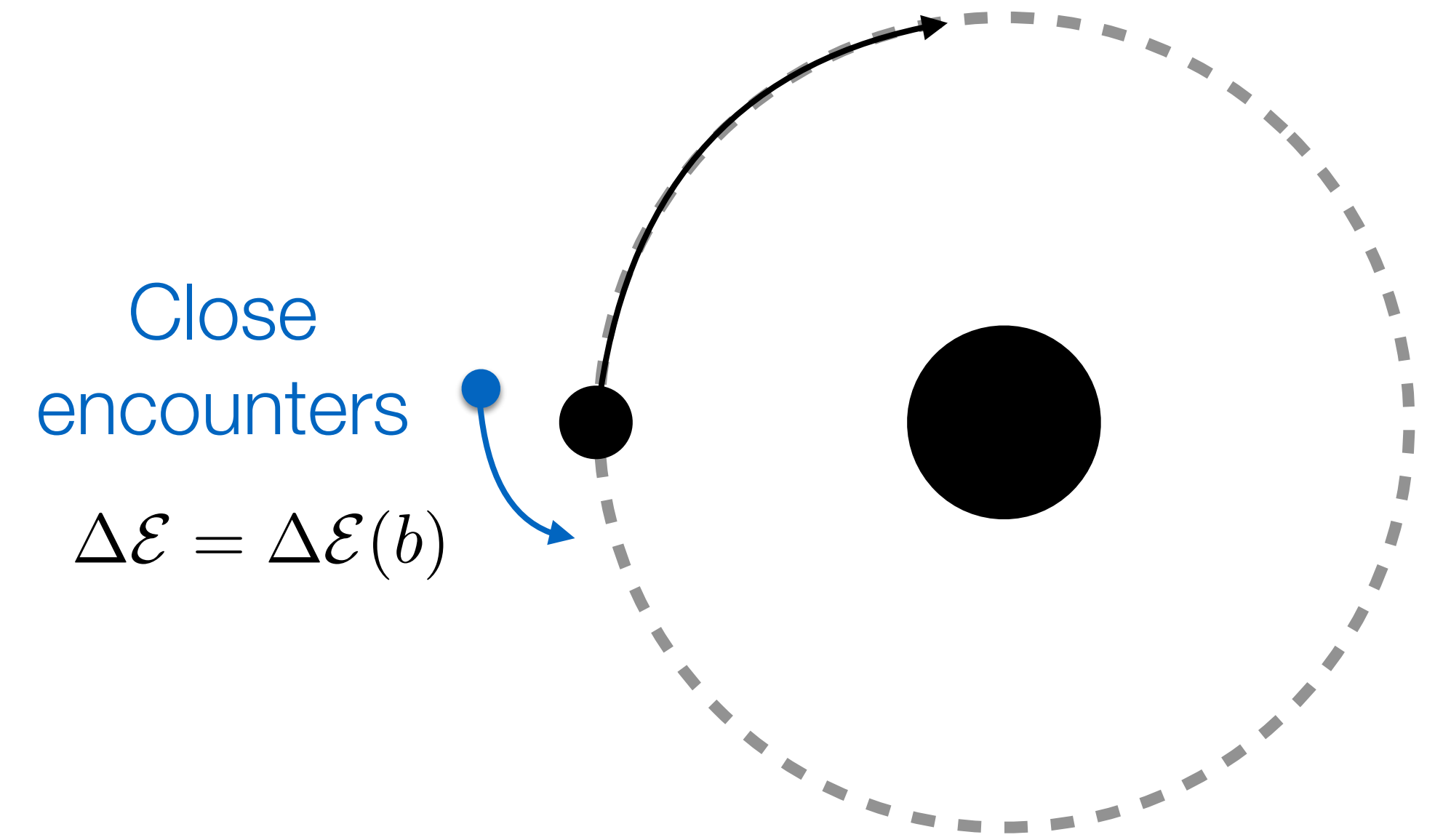
[See also Mukherjee et al., [2312.02275](#)]

N-body Simulations

N-body simulations revealed an additional feedback effect...



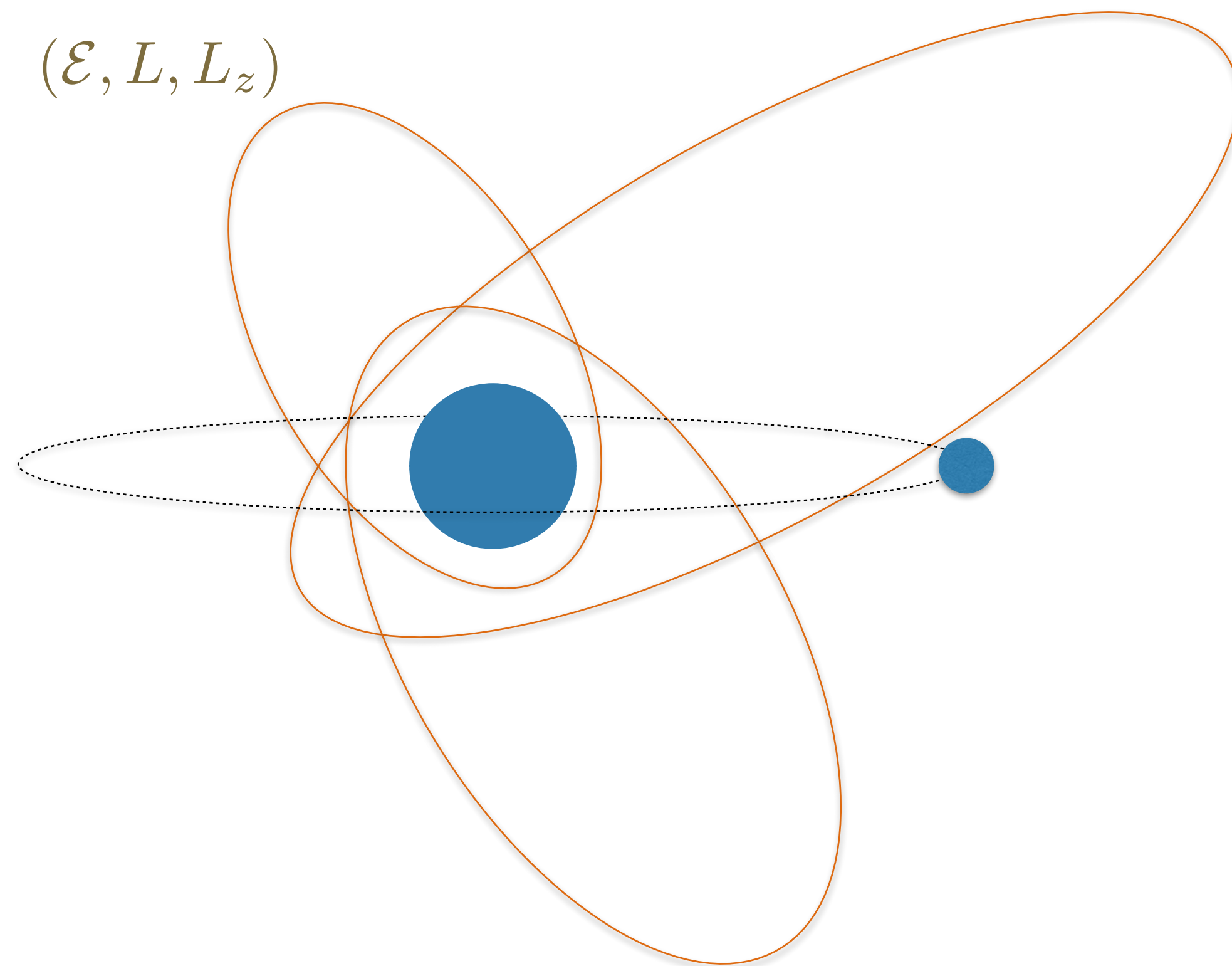
But N-body simulations are VERY slow!



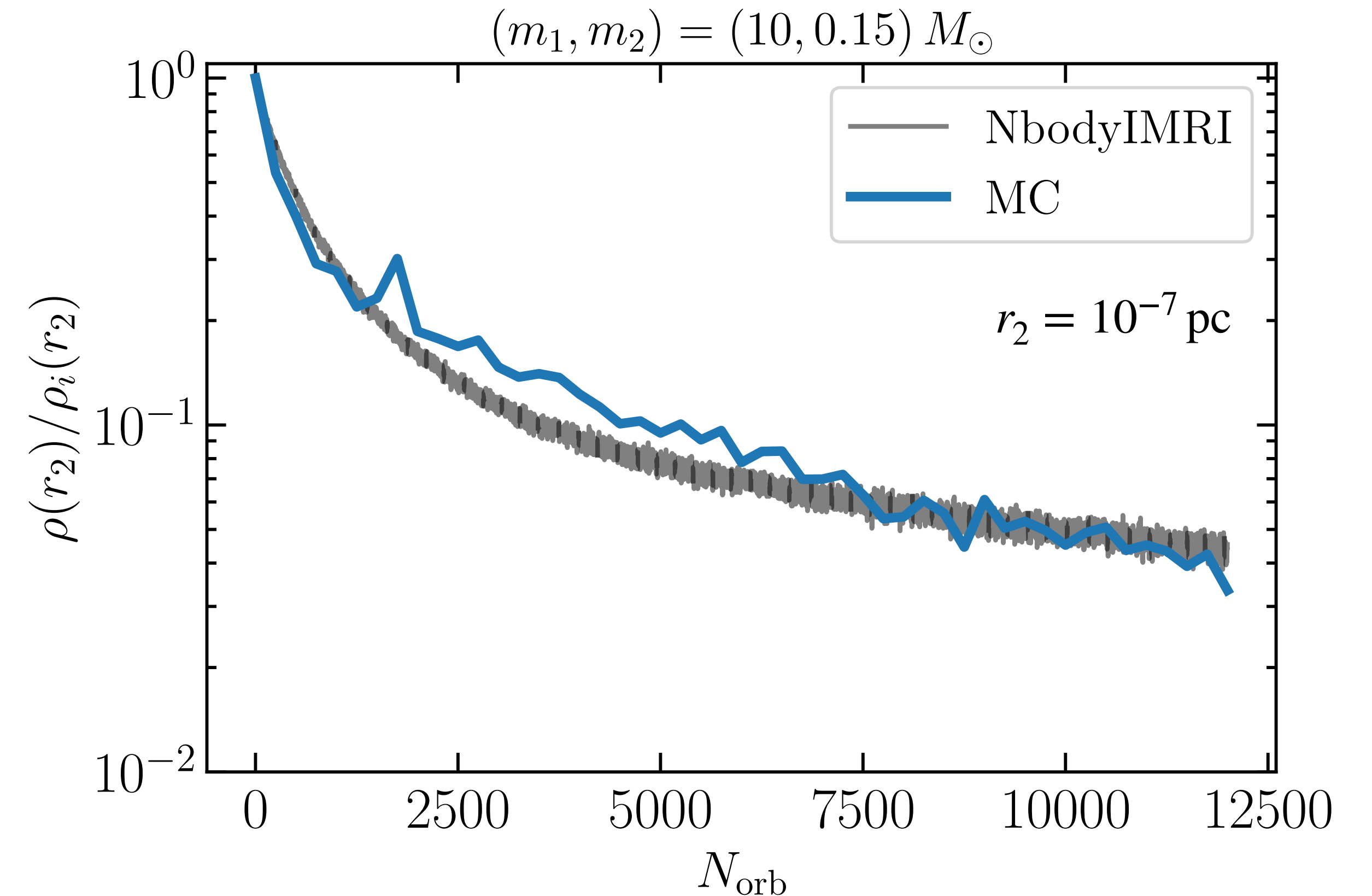
● 3-body 'stirring'

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t} dt$$

Phase-space Monte Carlo simulations, in which we track integrals of motion of DM particles $(\mathcal{E}, L, L_z)$.



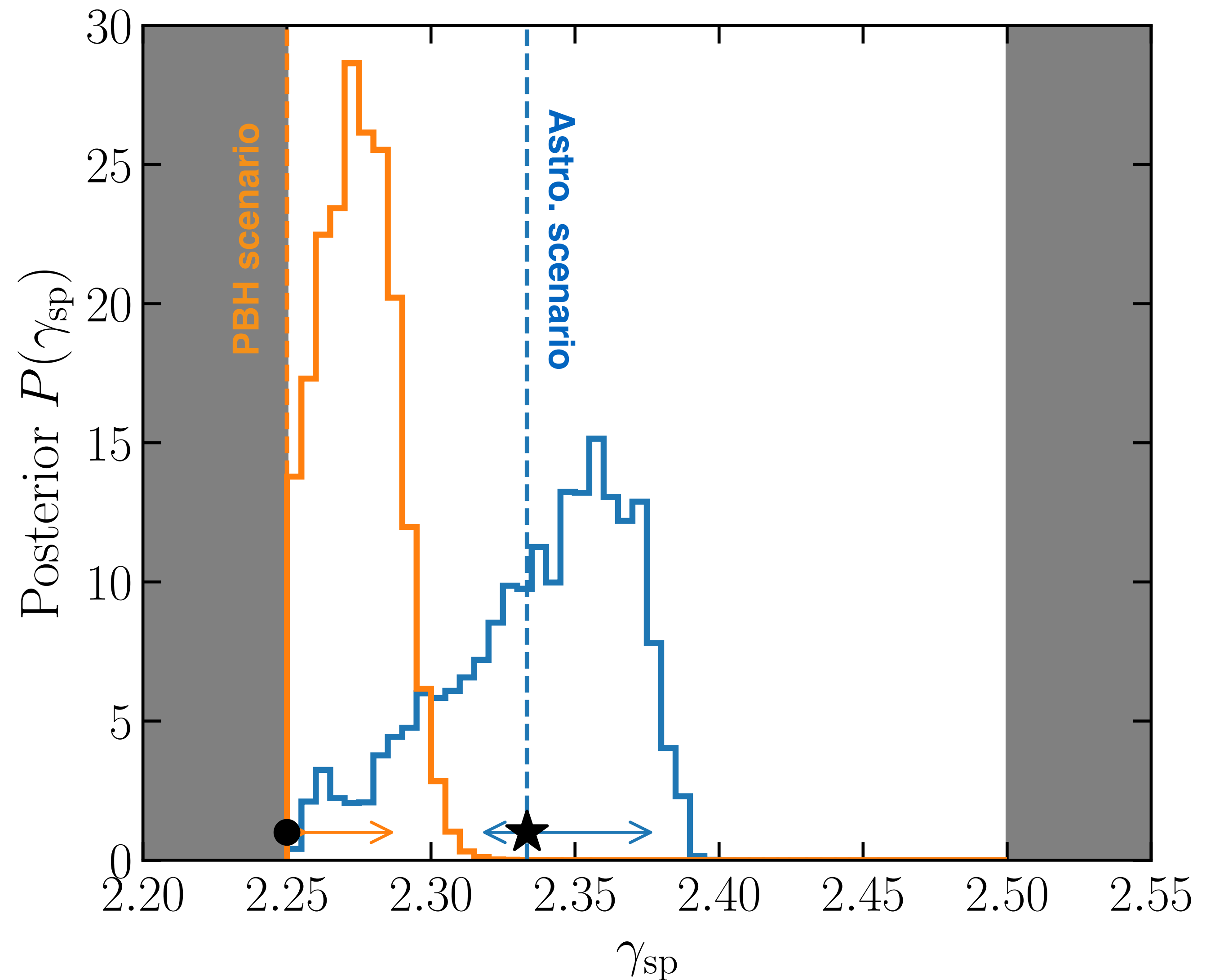
At each orbit of the binary, we apply a kick $(\Delta\mathcal{E}, \Delta L, \Delta L_z)$ due to close encounters ('dynamical friction') and due to 3-body effects ('stirring').

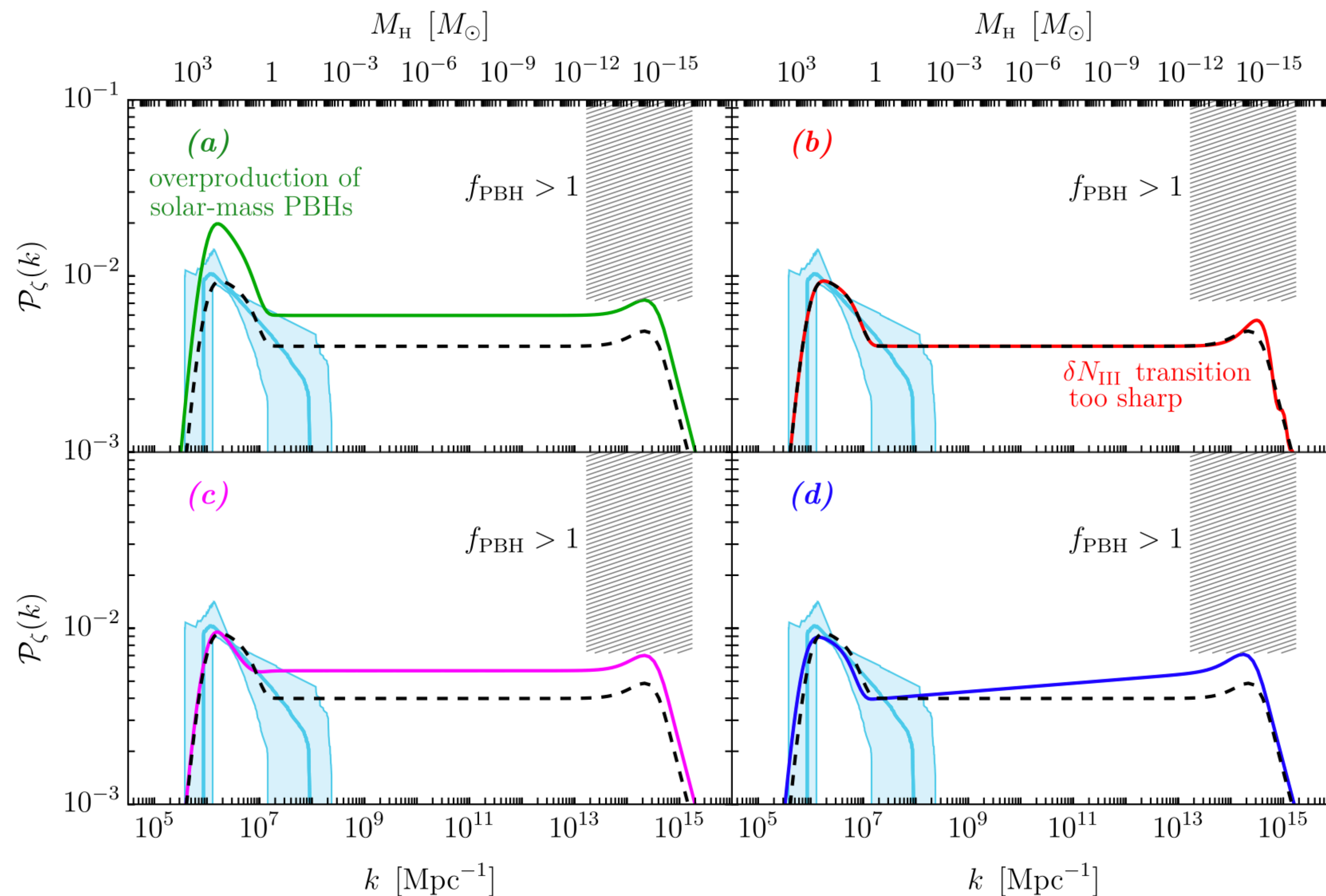


Can now self-consistently track the DM spike evolution!

We may be able to distinguish different *shapes* of spike

→ Different DM models and formation mechanisms!

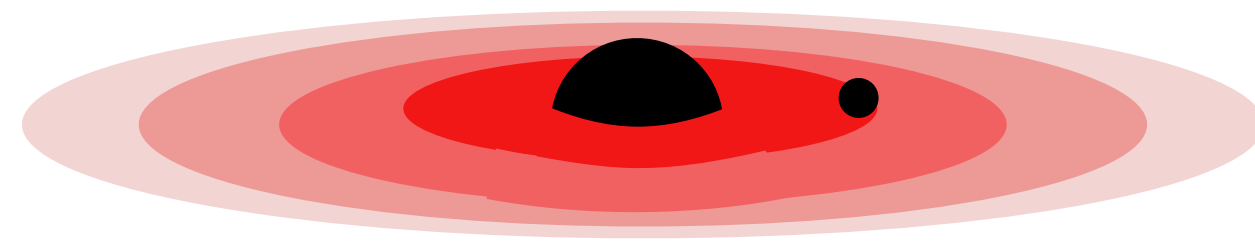




Environmental Confusion

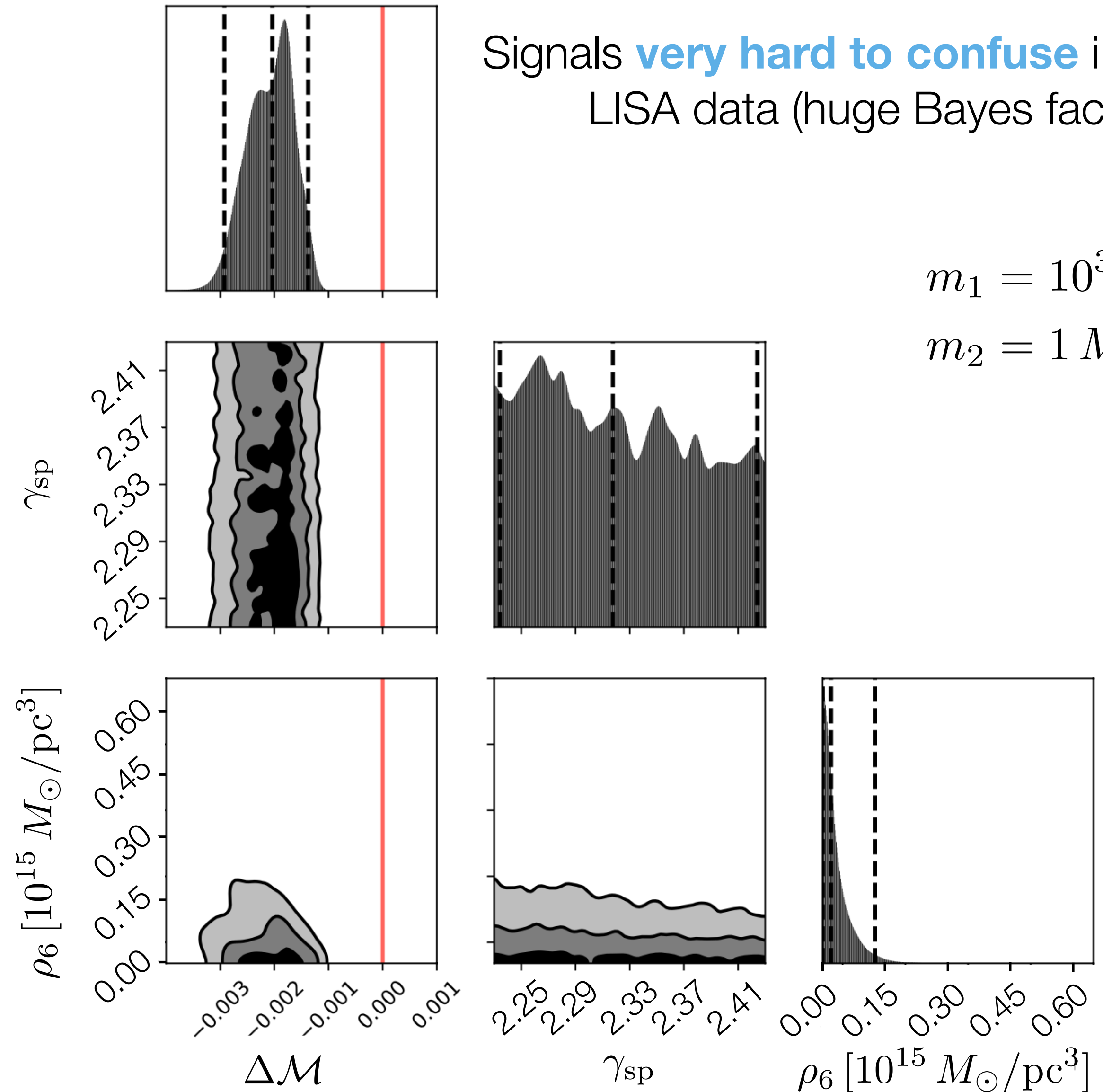
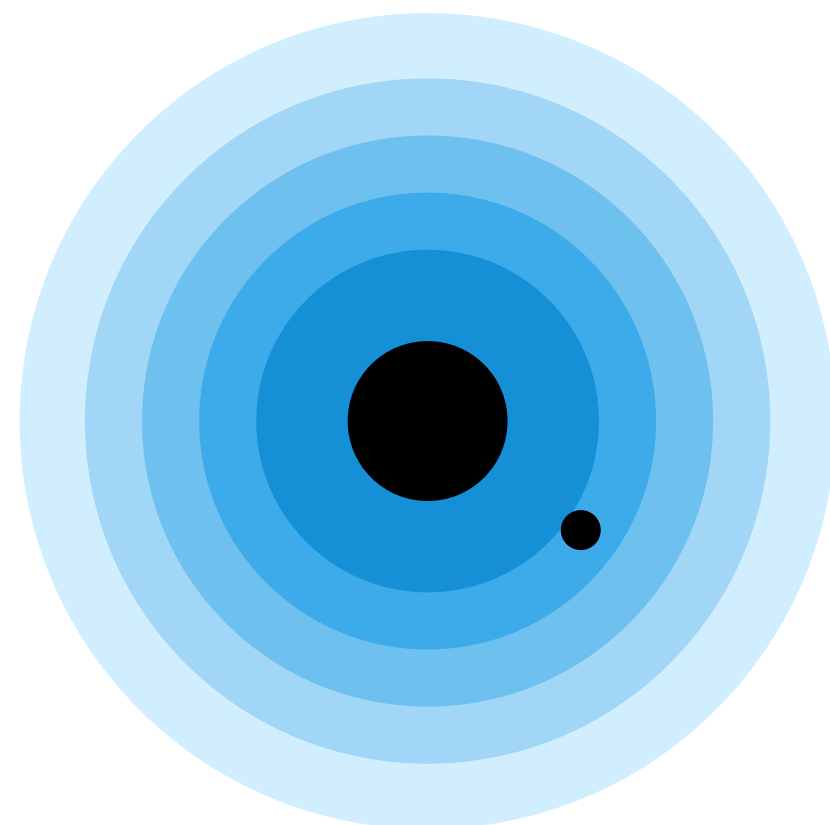
[Cole, Bertone, Coogan, Gaggero, Karydas, **BJK**, Spieksma, Tomaselli, [2211.01362](#), Nature Astronomy]

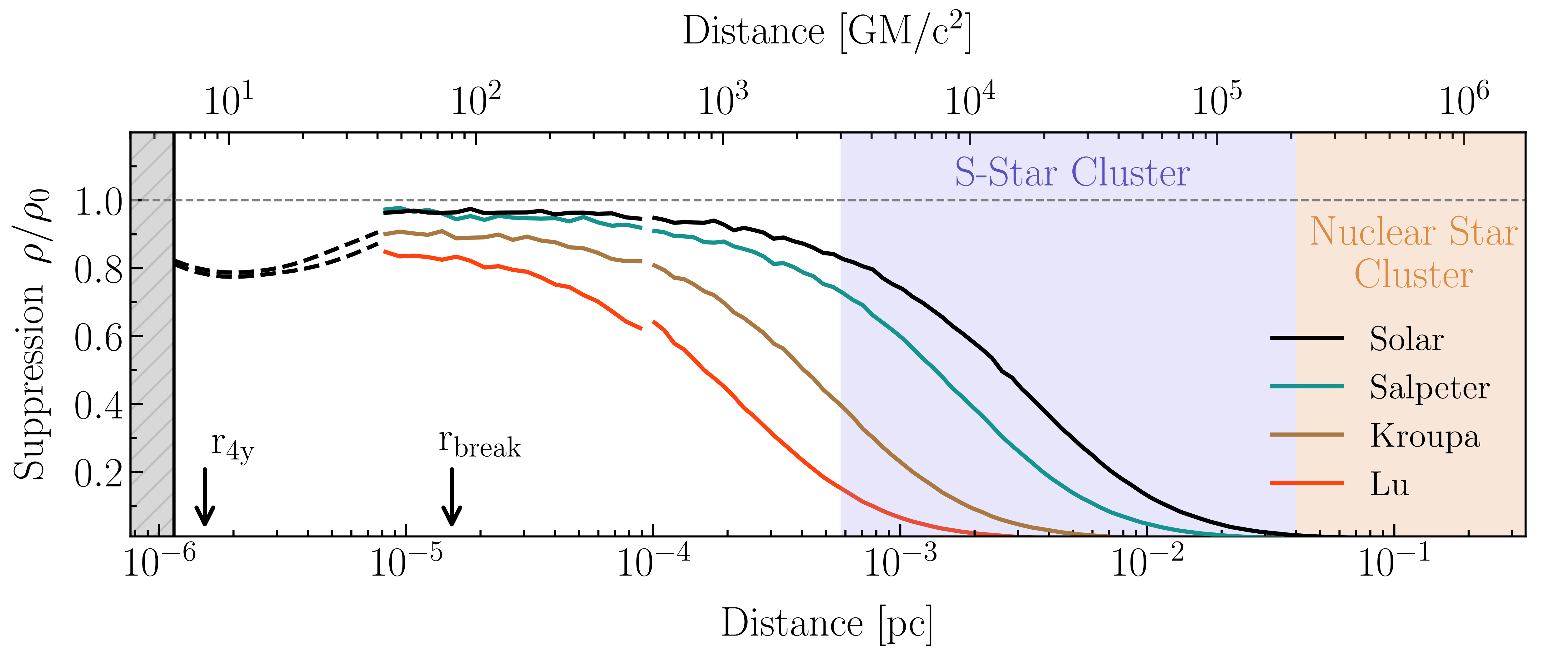
Generate waveform
assuming:



$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0} \right)^{-1/2}$$

Fit signal assuming:





Similar calculations could be applied to extra-galactic SMBHs.